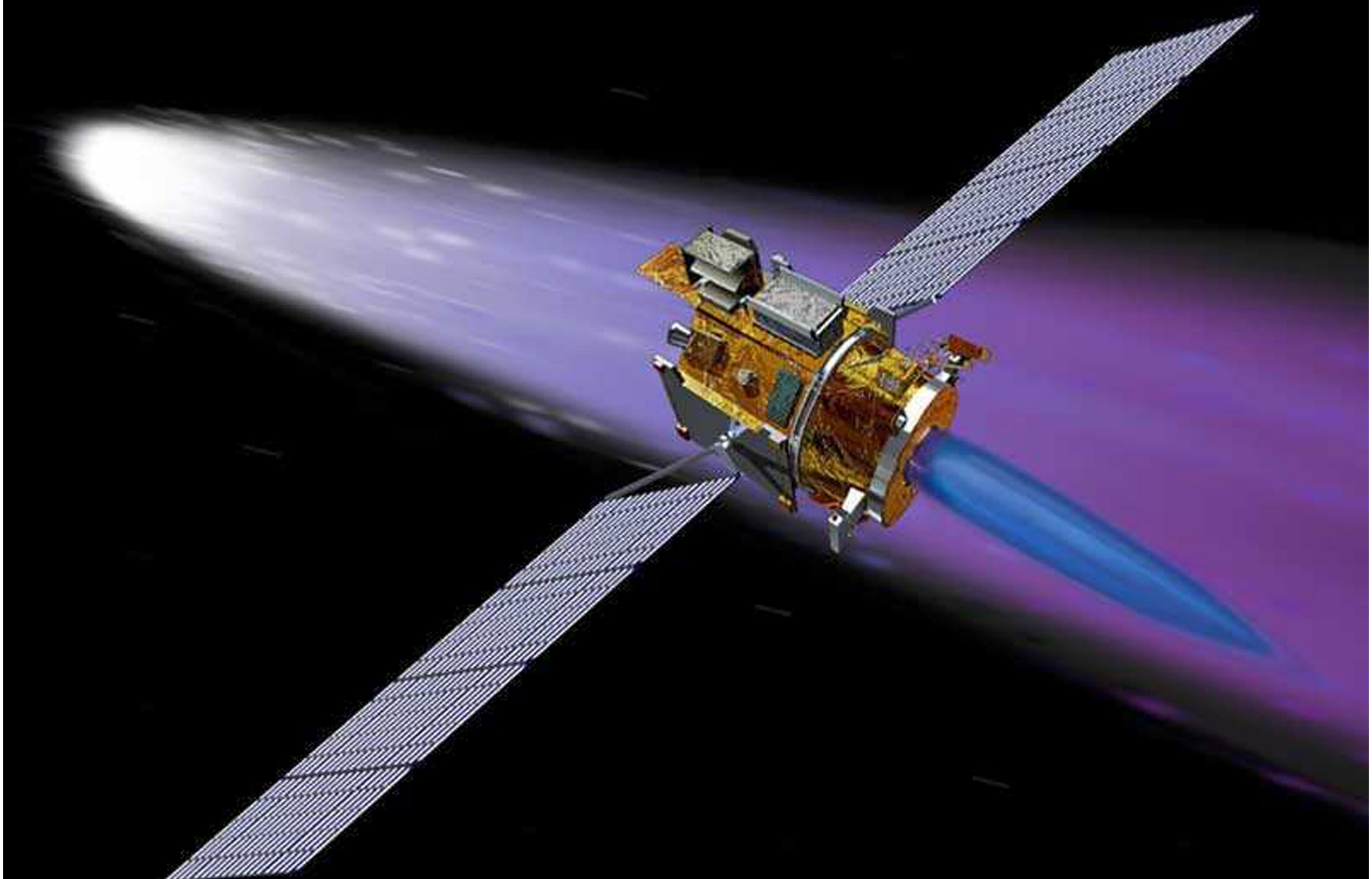
Deep Space 1

Telecommunications



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Article 2

Deep Space 1 Telecommunications

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Foreword

This Design and Performance Summary Series, issued by the Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO), is a companion series to the DESCANSO Monograph Series. Authored by experienced scientists and engineers who participated in and contributed to deep-space missions, each article in this series summarizes the design and performance for major systems such as communications and navigation, for each mission. In addition, the series illustrates the progression of system design from mission to mission. Lastly, it collectively provides readers with a broad overview of the mission systems described.

Joseph H. Yuen
DESCANSO Leader

Preface

This article describes how the Deep Space 1 (DS1) spacecraft and the Deep Space Network (DSN) ground systems receive and transmit data. The description is at a functional level, intended to illuminate the unique DS1 mission requirements and constraints that led to the communications-system design, and how the spacecraft has been operated in flight.

The primary purpose of this article is to provide a reasonably complete single source from which to look up specifics of DS1-radio communications. The References and Additional Resources sections include external as well as internal Jet Propulsion Laboratory (JPL) articles and web sites. The article is a record of the DS1-mission telecommunications (telecom) through August 2001, and was written and reviewed by JPL telecom people involved with DS1 design and flight, and JPL's New Millennium program office.

Much of the telecom-design information in this article comes from the *DS1 Telecom Operations Reference Handbook*, written by Chien-Chung Chen [1]. The telecom-technology description originated from a February 2000 DS1 technology-validation symposium at JPL and the Master of Space Studies theses submitted to the International Space University by two of the authors [2], who interned at JPL in 2000 and 2001 as part of 12-week NASA/JPL/ISU-sponsored programs.

Acknowledgments

The authors would like to express their appreciation to Gael Squibb in the InterPlanetary Network and Information Systems Directorate (IPN-ISD) for his encouragement and support during the preparation of this article.

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Section 1

Mission and Spacecraft Description

1.1 Technology Validation

DS1* is the first of the New Millennium Program (NMP) deep-space technology-validation missions. The development of DS1 was led by JPL, with Spectrum Astro, Inc. as the industry partner for spacecraft development.

DS1's payload consists of 12 advanced technologies for deep space that flew for the first time. With the three involving telecom listed first, the DS1 technologies are:

- Small Deep Space Transponder (SDST) for X-band uplink and X- and Ka-band downlink
- Ka-band solid-state Power Amplifier (KaPA) and associated experiments in Ka-band carrier tracking, telemetry demodulation, and turnaround ranging
- Beacon Monitor Operations Experiment (BMOX) for autonomous onboard health and status summarization and request for ground assistance
- Miniature Integrated CAmera Spectrometer (MICAS), a panchromatic visible imager and infrared and ultraviolet imaging spectrometers
- Solar-electric propulsion (SEP) technology, implemented as the Ion-Propulsion System (IPS)
- Autonomous onboard navigation (AutoNav)
- Solar-Concentrator Arrays, using Refractive Linear Element-Technology (SCARLET)
- Integrated ion-and-electron spectrometer, known as the Plasma Experiment for Planetary Exploration (PEPE)
- Remote Agent eXperiment (RAX) architecture for autonomous-onboard planning and execution

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

- Set of Low-Power Electronics (LPE)
- High-packaging-density smart power switch, known as a Power-Actuation and Switching Module (PASM)
- Multi-Functional Structure (MFS) experiment combining electronics and thermal control in a structural element.

Although there are 12 advanced technologies on DS1, the rest of the spacecraft payload is composed of current, low-cost components that have been tried and tested on other missions. For example, the high-gain antenna (HGA) is a flight spare from the Mars Pathfinder program, and the flight computer is based on that used by Mars Pathfinder [3].

This approach—combining new technologies with tried-and-true components—is being used because the New Millennium Program focus has been to prove that certain advanced technologies work in space, not to build a spacecraft out of advanced but unproven components.

1.1.1 Mission Overview

DS1 was launched October 24, 1998 [4] and is in its extended mission [5]. The DS1 primary-mission design and execution focused exclusively on the validation of the 12 new technologies [6]. Technology testing was completed two weeks before the encounter with Asteroid 9969 1992KD (renamed Braille shortly before the encounter) on July 29, 1999 [5]. As a bonus to its technology-validation mission, DS1 collected a wealth of science data. The MICAS instrument recorded pictures and spectra of Mars, Jupiter, and selected stars. PEPE recorded extensive solar-wind data, some in collaboration with the Cassini spacecraft.

The primary mission concluded, having met or exceeded all of the mission success criteria, on September 18, 1999.

The extended mission's goal, in contrast to technology validation, was to return science data from the encounter with comet Borrelly on September 22, 2001.[1] The primary challenge in the extended mission was working around the failure in November 1999 of the star tracker, or stellar-reference unit (SRU). By June 2000, the flight team had devised a major revision of the flight software to use the science camera (MICAS) as a substitute for feeding star data to the attitude-control system. After that, project-mission planning had also accommodated a solar conjunction (spacecraft on the opposite side of the Sun from Earth) in November 2000, and another flight-software update in March 2001 to improve the probability of acquiring remote-sensing data during the Borrelly encounter.

For telecom operations, the DS1 flight team initially responded to the onboard SRU failure by substituting from the ground in near-real time, downlink carrier-signal observation, telecom analysis, and uplink control. The replaced functionality achieves pointing the body-mounted HGA to within an acceptable angle of Earth. The "HGA activity" [7], described more fully later, is labor-intensive and exacting in timing requirements. The RTLT (round-trip light time) delay in the HGA activity's downlink signal monitor and corrective-command transmission

[1] The original plan for the extended mission was for a flyby of the comet Borrelly [5]. During technology validation, as we learned how and how well the spacecraft worked, we added a flyby of comet Wilson-Harrington for early 2001. The SRU failure and the recovery from that resulted in an extended period without IPS thrusting and a consequent replanning of the mission for a Borrelly flyby only.

process is manageable. The RTLT was about 30 min. in early 2000, 40 min. at solar conjunction, 34 min. during the March 2001 software update, and was about 25 min. during the Borrelly encounter.

Following the successful flyby of the comet Borrelly, DS1 began what has been named the hyperextended mission. This final mission phase, which includes some additional technology validation of the IPS and the KaPA, will end with the spacecraft's downlink being shut off in December 2001.

1.1.2 Telecom System Overview

By project policy, and like other parts of the spacecraft, the DS1 telecom system is "single string" (without block redundancy). The system elements include a transponder (receiver-transmitter in which the downlink can be phase-coherent with the uplink), power amplifiers for X- and Ka-band, and selectable directive and wide-beamwidth antennas. See Figs. 3-1 and 3-2 in Section 3.

The primary communication link is on Channel 19 at X-band (7.168-GHz uplink and 8.422-GHz downlink). The SDST includes the X-band receiver, command-detection and telemetry-modulation functions, and X- and Ka-band exciters.[2] The X- and Ka-band solid-state power amplifiers (XPA and KaPA) provide 12 W of RF power at X-band, and 2.2 W at Ka-band.

The Ka-band downlink carrier, phase coherent with the X-band downlink carrier, is also on Channel 19 (32.156 GHz). The Ka-band carrier can be unmodulated, or modulated with telemetry or ranging data like the X-band carrier.

DS1 has four X-band antennas. The high-gain antenna has a half-power beamwidth[3] of about ±4.0 deg, and ±4.5 deg on the downlink and uplink, respectively. The three low-gain antennas are pointed along different spacecraft axes and have beamwidths of about ±35 deg for both downlink and uplink. As controlled through waveguide-transfer switches, the X-band uplink and downlink are always on the same antenna.

The Ka-band downlink is transmitted from the KHA (Ka-band horn antenna), which has a half-power beamwidth of about ±3.5 deg.

[2] "Exciter" is a generic term for the portion of a radio transmitter that produces the carrier frequency. The SDST has two exciter functions, one for X-band and the other for Ka-band. Besides generating the output carrier frequency, each exciter also has a phase modulator and the modulation index control for each kind of downlink modulation.

[3] The direction of maximum gain of an antenna is called the boresight. The half-power beamwidth is defined in terms of the angle from boresight at which the antenna would have the capability to transmit (or receive) half as much power as at the boresight. In this article, to avoid ambiguity, the half-power beamwidth is expressed in terms of ± deg from boresight. A half-power beamwidth of ±4 deg would be a total beamwidth of 8 deg.

Section 2

Telecom System Requirements

The DS1* development-phase project policies and top-level requirements led to a number of high-level directives regarding system implementation. DS1 was intended as a capability-driven—as opposed to science-driven—mission.[1]

Spacecraft- and ground-system designs were driven strongly by existing hardware, software, and system capabilities in order to meet cost, schedule, and risk constraints:

- Capability-Driven Design: High-level requirements could be renegotiated (requirements reduced) if they conflicted with understood capabilities of existing hardware
- Single-String Implementation: The project policy identified that a single-string design was to be employed unless an existing design already incorporated redundancy.

For telecom, these constraints resulted in flying a single unit of each of two advanced technology subsystems: the SDST and the KaPA. The SDST is a flight-engineering model (FEM), as project development and test schedules precluded a full flight model.

Except where functional redundancies already existed (for example, telemetry available on either X- or Ka-band downlink, and X-band downlink available via either high- or low-gain antenna), project policy precluded "conventional" backups for these functions. Furthermore, it was project policy to employ single-string design, and avoid cross-strapped redundancy unless existing designs (off-the-shelf or advanced technologies) already had it, and it was cost-effective to retain it.

Unlike a traditional science-driven mission, DS1 imposed fewer absolute link-performance requirements (such as minimum downlink rate vs. time) that the telecom system had to meet. Nevertheless, a number of issues imposed requirements on the telecom system.

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[1] "Science-driven" means the requirements that define a scientific mission govern the design of the spacecraft, its mission design, and its ground system. Capability-driven means that the requirements placed on the spacecraft, etc., follow from (rather than determine) the definition of hardware and software systems that are available.

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*Look up this and other abbreviations and acronyms in the list that begins on page 60.

Sources of these system requirements were:

- Project policies
- Mission-coverage needs
- Technology-validation goals
- End-to-end information-flow considerations
- Interoperability with the DSN
- Spacecraft-architecture constraints
- Radiometric-tracking accuracy.

The above considerations led to the definition of the flight-system (spacecraft) telecom requirements. Top-level telecom-system capabilities and link design to meet the requirements are defined in the DS1 Project Requirements/TMOD Support Agreement (PR/TSA) [8]. SDST parameter values measured during prelaunch testing are in the "Telecommunication FEM SDST/DSN compatibility and performance Motorola test report"[9].

Section 3

Telecom System Description

The DS1* telecom system provides X-band uplink and X/Ka-band downlink capabilities to handle all RF communications between the DS1 spacecraft and the DS1 mission operations team via the DSN. The telecom system receives and demodulates uplink commands, transmits science- and engineering-telemetry data on either an X-band or a Ka-band downlink or both, and provides coherent two-way Doppler and range-measurement capabilities using the X-band uplink, and the X- or Ka-band downlink. Figure 3-1 is a block diagram of the telecom-system functional elements.

DS1 has four antennas that operate at X-band (one HGA and three LGAs) and one Ka-band antenna (the KHA). Figure 3-2 shows the antenna locations on the spacecraft. Each antenna has a direction of maximum gain, often called the boresight. The boresights of the HGA, LGAX, and KHA are parallel to the +x-axis. The boresights of LGAZ+ and LGAZ– are parallel to the +z-axis and the –z-axis, respectively. Orienting the DS1 spacecraft so that the +x-axis points at Earth maximizes the performance of links using the HGA, LGAX, or KHA. All antennas are right-circularly polarized (RCP) except LGAZ–, which is left-circularly polarized (LCP).[1]

Figure 3-3 shows the downlink pattern of each LGA; Fig. 3-4 shows the X-band downlink pattern of the HGA. The X-band uplink patterns are similar, but slightly broader because of the lower-uplink frequency. Figure 3-5 shows the KHA pattern.

[1] The LGAZ– antenna element is a duplicate of LGAZ+, mounted midway out on the service boom, with its boresight oriented along the –z-axis. LGAZ– was added to the spacecraft late in the development phase, less than one year before the planned launch date. The need for the antenna was in the first weeks after launch, when the range was small (strong signals) but Earth-spacecraft geometry would result in blockage of signal paths to LGAX or LGAZ+. Antenna-system design needed to preserve the capability of LGAZ+ as much as possible, and at the same time disturb the existing configuration and spacecraft system interfaces as little as possible. These needs led to the choice of a passive vs. an active-coupling system, and to a 25 percent/75 percent power split between the LGAZs.

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

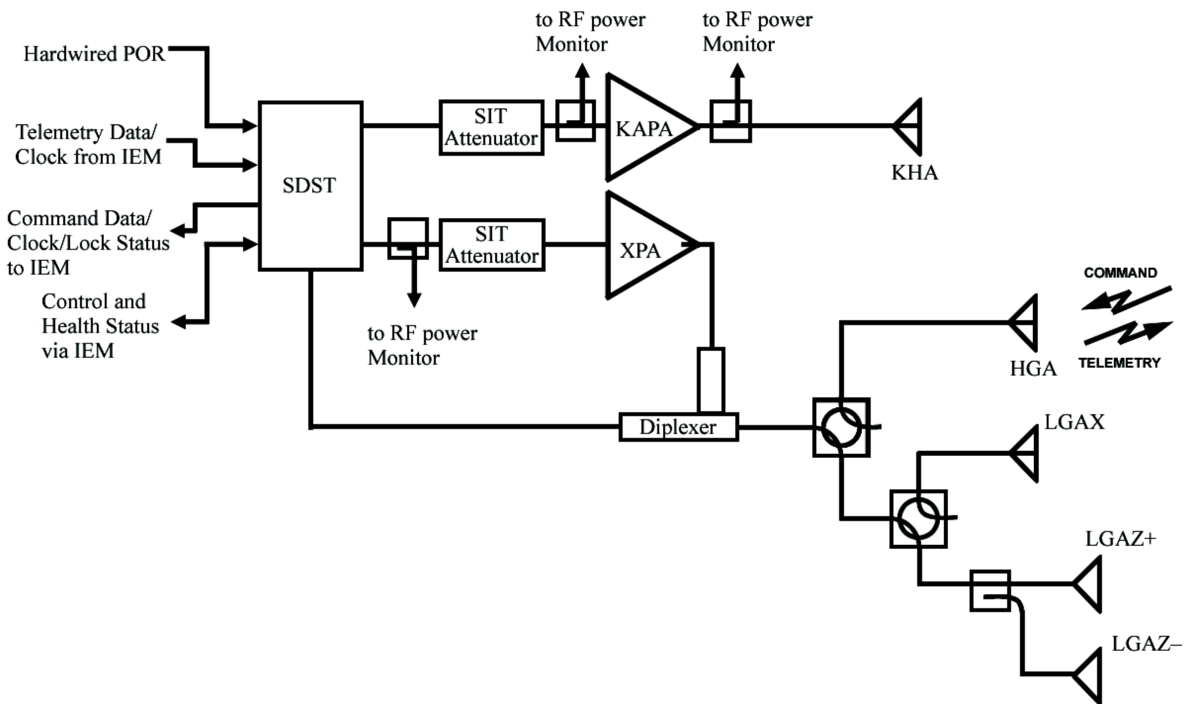

Fig. 3-1. DS1 spacecraft telecom system functional block diagram.

The SDST provides the detected-command bits for decoding and an in-lock/out-of-lock indicator to the Integrated Electronics Module (IEM) of the avionics system. The IEM can send a power-on-reset (POR) signal to the SDST to activate a relay to remove spacecraft power from the SDST for 3 s, and then restore power. The SDST receives a serial stream of telemetry-data bits and a clock signal from the IEM.

The amount of RF power that is input to the XPA from the SDST X-band exciter is established by a “select in test” (SIT) attenuator. Similarly, a SIT attenuator establishes the KaPA’s input RF-power level. A 6-dB passive coupler connects the two z-axis LGAs, making both LGAZ+ and LGAZ– active when “the LGAZs” are selected for X-band. This means that (on the downlink) RF energy radiates out of both antennas when the LGAZs are selected, with the 6-dB coupler sending 25 percent of the energy to LGAZ–.

The HGA has a larger on-boresight gain than any LGA, but also a narrower pattern. When the spacecraft x-axis can be kept within 6 deg of Earthline, the HGA is selected (it has 15 dB more gain than the XLGA). Otherwise, the spacecraft is commanded or sequenced to operate on either LGAX (aligned with the +x-axis) or on the system of LGAZ+ and LGAZ– (aligned with the +z- and –z-axis, respectively).

The three LGAs all have the same patterns of gain as a function of angle from boresight. Because of different circuit losses between the SDST and each antenna, LGAZ+ has an effective gain about 1.5 dB lower than LGAX, and LGAZ– about 7 dB lower than LGAX. Much of the in-flight telecom analysis involves what uplink- or downlink-data rates are available for different conditions of spacecraft pointing and antenna selection.

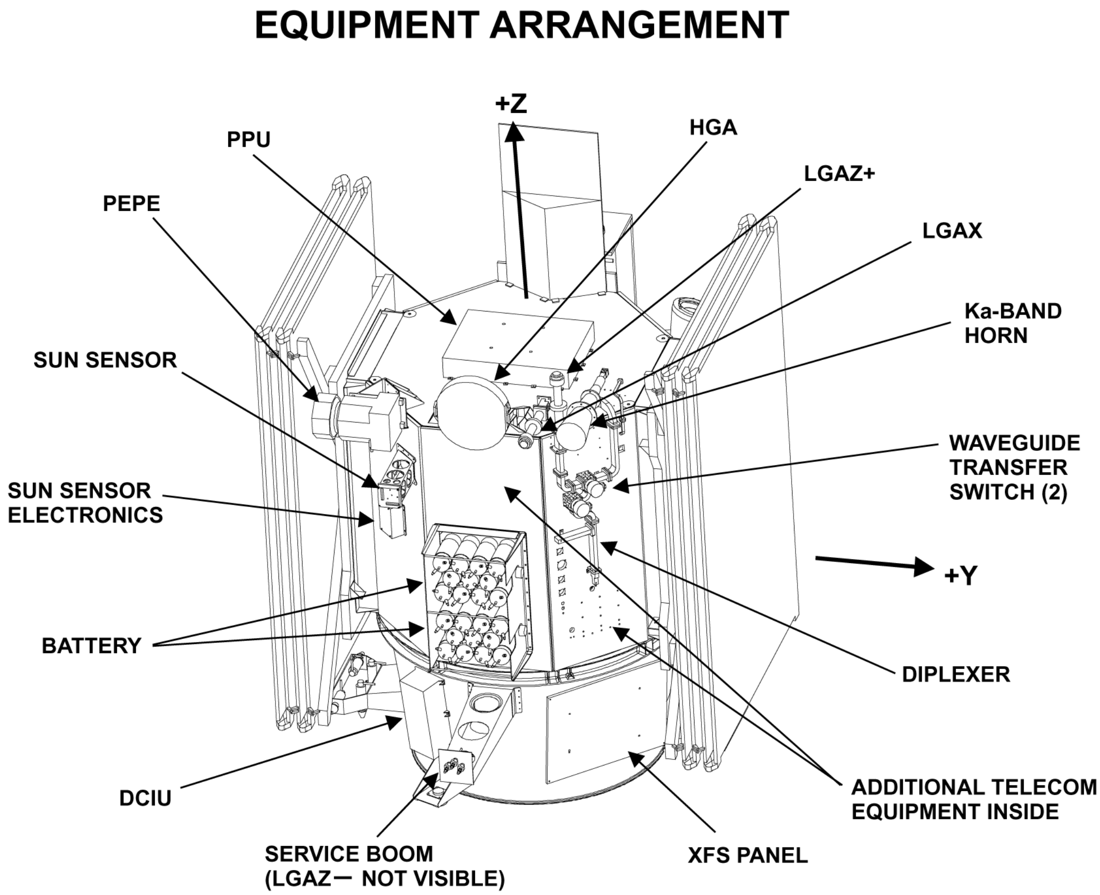

Fig. 3-2. Launch mode configuration, with telecom system components.

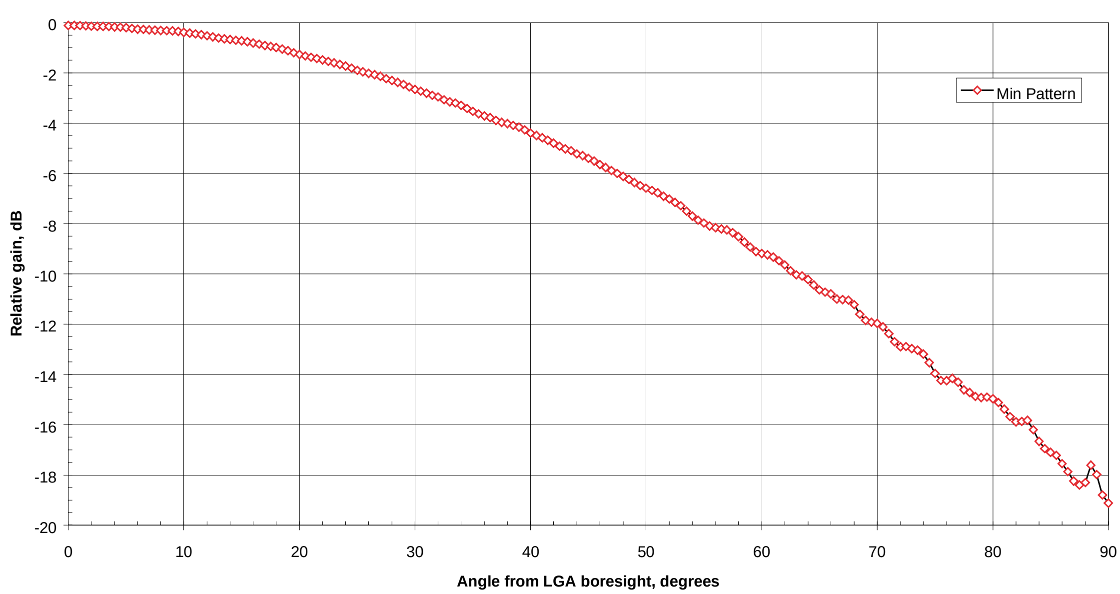

Fig. 3-3. LGA downlink pattern (relative gain as a function of angle from boresight).

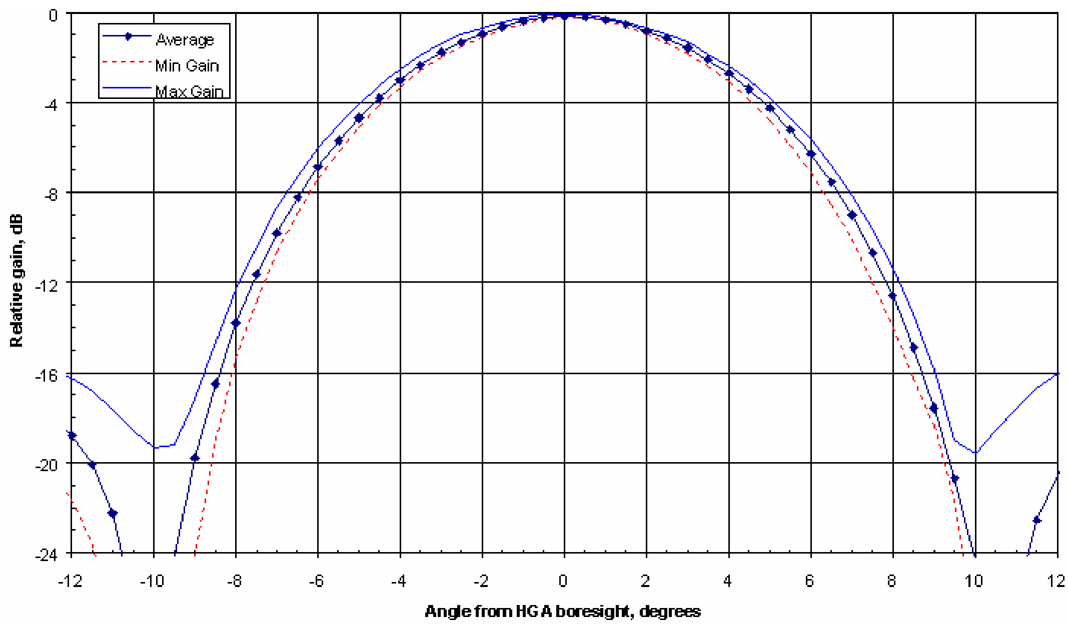

Fig. 3-4. HGA downlink pattern (relative gain as a function of angle from boresight).

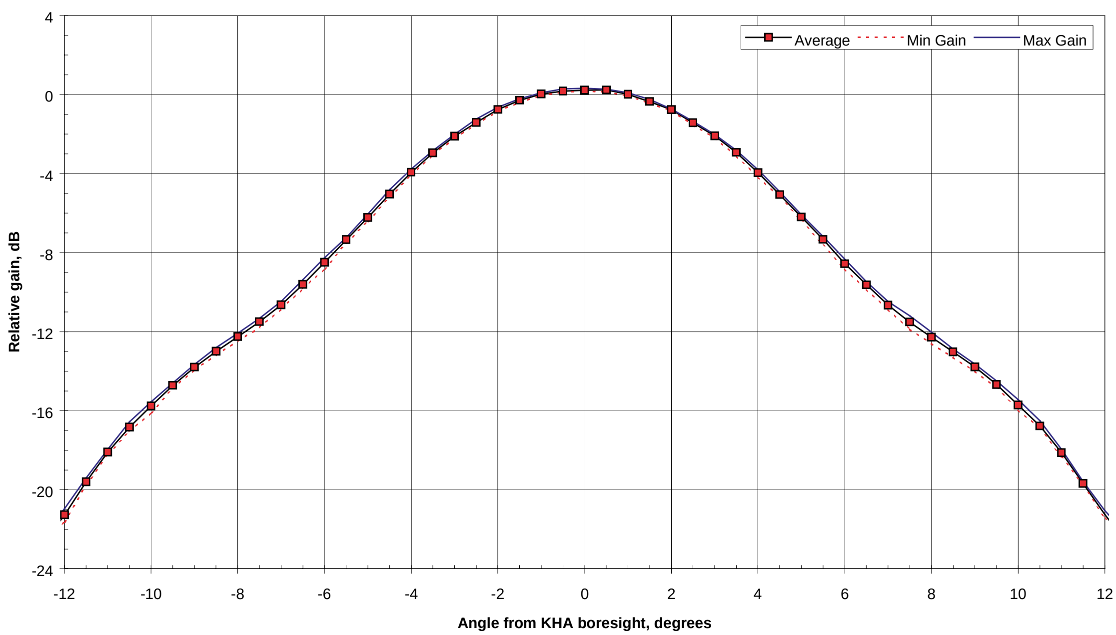

Fig. 3-5. KHA pattern (relative gain as a function of angle from boresight).

Section 4

DS1 Telecom Technology

The three telecom-related technologies [6] demonstrated during the DS1* prime mission are:

- Small Deep-Space Transponder
- Ka-Band Power Amplifier
- Beacon Monitor Operations Experiment.

4.1 Small Deep-Space Transponder

The Small Deep-Space Transponder (SDST) (Fig. 4-1) is designed to facilitate command, telemetry, and radiometric communication between mission control and the spacecraft. The SDST combines the spacecraft receiver, command detector, telemetry modulator, turnaround-ranging channels, exciters, and control functions into one 3-kg package. Developed by Motorola, Inc., Scottsdale, Arizona, under funding from NASA's Jet Propulsion Laboratory, SDST provides a spacecraft terminal for X- and Ka-band signals with the NASA DSN, allowing X-band uplink, and X- and Ka-band downlink. It also provides coherent and noncoherent operation for radionavigation purposes. This compact, low-mass transponder is enabled by the use of advanced GaAs (gallium arsenide) monolithic microwave-integrated circuits.

As the heart of the telecom system, SDST performs the following key functions.

4.1.1 Uplink-Receiving Functions

- Receive and demodulate the X-band-uplink carrier
- Provide an uplink AGC (automatic gain control) function for receive-power control and measurement
- Receive and demodulate the command subcarrier and data stream.

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

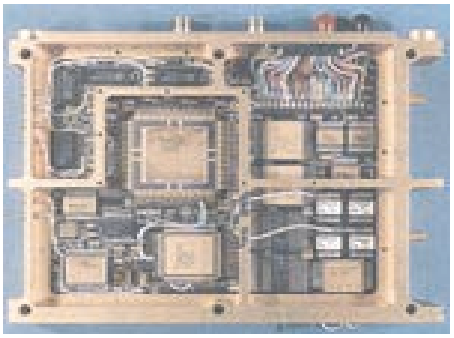

Fig. 4-1. The Small Deep-Space Transponder (SDST).

4.1.2 Downlink-Transmitting Functions[1]

- Generate a noncoherent downlink with auxiliary oscillator or ultrastable oscillator (USO)
- Perform convolutional encoding[2] and subcarrier modulation of the downlink telemetry
- Modulate X- and Ka-band carriers with telemetry subcarriers or directly[3]
- Provide independent control of X- and Ka-band modulation-index values.

4.1.3 Radio Metrics

- Generate two-way coherent downlink carriers by phase locking with uplink signal[4]
- Demodulate uplink-ranging signal and remodulate signal on the downlink
- Provide differential one-way ranging (DOR) tones for downlink.

4.1.4 SDST Performance Monitoring and Spacecraft Data Interfaces

- Receives commands from the Integrated Electronics Module (IEM)
- Collects analog-engineering status within the system
- Provides status and performance parameters to the IEM.

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[1] Three of the SDST capabilities in these lists were not planned for operational use by DS1. DS1 does not have a USO and, therefore, the SDST auxiliary oscillator always provides the one-way-downlink carrier. Telemetry modulation is in the subcarrier mode only. DOR (differential one-way ranging) tones were checked out but not used for navigation during the prime mission technical validation. Late in the extended mission, the project scheduled and made use of DSN operational delta-DOR navigation data twice in the week prior to the September 22, 2001 Borrelly encounter.

[2] See Section 6 for a description of the telemetry-transfer frame, which is convolutionally encoded by the SDST.

[3] See note 1 above.

[4] DS1 operates on DSN channel 19, with frequencies as defined in the PR/TSA (Project Requirements/TMOD Support Agreement) [8] and in JPL document 810-005 [12]. The defined X-band-downlink frequency (8.422 GHz) is 880/729 times the defined X-band-uplink frequency (7.168 GHz). The defined Ka-band-downlink frequency (32.156 GHz) is 3360/749 times the X-band-uplink frequency.

- SDST design accommodates interfaces with spacecraft avionics via either a MIL-STD-1553, MIL-STD-1773, or RS422 serial bus, using the 1553 protocol. This design allows future SDST users the maximum flexibility of selecting the system architecture. The DS1 SDST Command and Data Handling (C&DH) communication is via the 1553, and the data interface uses the RS422 [6].

Technology-validation, link-performance tests for SDST (and the KaPA, below) included transmitting each of the 19 DS1 telemetry rates simultaneously over X- and Ka-band to verify that the station could lock up to and decode data at each rate. The ranging channel was operated at low- and high-modulation index values, and the received-range delay compared between the two bands. Frequency-stability and carrier-noise levels (both affecting Doppler data quality) were compared between the bands. The SDST DOR modulation was turned on briefly to verify its operability.

As a result of DS1's success in proving the SDST design in flight, the recently launched Mars'01 Odyssey, the in-development Mars'03 Exploration Rover (MER), and Deep Impact (DI) missions are using the SDST. There is a group-buy where several JPL missions (MER, DI, ST3) are pooling their resources to buy SDSTs.

4.2 Ka-Band Solid-State Power Amplifier (KaPA)

4.2.1 KaPA and Ka-Band Overview

At DS1 launch, the KaPA (Fig. 4-2) was the highest-power deep-space solid-state Ka-band amplifier yet flown. The KaPA developed by Lockheed Martin Communication and Power Center, operates at 32 GHz and weighs 0.7 kg. As established during in-flight-technology validation, the KaPA amplifies the RF output from the SDST Ka-band exciter to 2.2 W with an overall efficiency of 13 percent [6].

The group-buy mentioned with regard to the SDST includes Ka-band for some of the missions.

Ka-band offers a potential link-performance advantage for deep-space communications. With future improvement of ground facilities and spacecraft hardware, assuming similar power

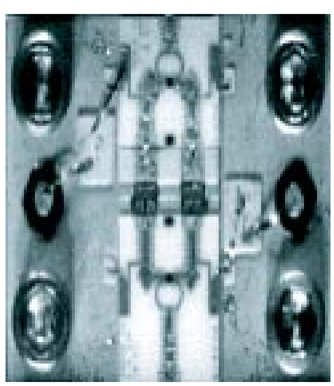

Fig. 4-2. Ka-band power amplifier (KaPA).

efficiencies and spacecraft antenna sizes, Ka-band holds a potential four-fold increase in data rate compared to X-band. This fact alone is obviously important as at the end it means reduced project cost. Ka-band offers greater available bandwidth as NASA and other agencies move away from lower frequencies shared with personal communications systems and other emerging information-technology ventures.

On the debit side, the need for a KaPA/Ka-band technology demonstration on DS1 speaks to the relative maturity of flight systems at this frequency, in contrast to X-band. Ka-band link performance is also more sensitive than X-band to clouds and rain, which is a challenge to designing reliable deep-space Ka-band links. Arrays that take into consideration different seasonal weather patterns at each DSN longitude (e.g., California and Arizona) can increase link reliability. Once necessary Ka-band ground systems are in place, a higher-data rate requires fewer ground resources and less mission-operation support per spacecraft-operation week.

4.2.2 KaPA and Ka-Band In-Flight Technology Validation

As part of the technology validation, DS1 first successfully demonstrated the KaPA in flight less than two months after launch and has operated it to benefit ground-systems development as recently as March 2001. On December 9 and 10, 1998, the SDST Ka-band exciter and the KaPA were first powered on in flight. During two passes, the Ka-band link functions were methodically verified. These functions (also tested with the X-band downlink) included coherent and noncoherent downlink carrier tracking, turnaround ranging, and telemetry decoding at all DS1 downlink rates.

KaPA engineering-telemetry measurements were confirmed as nominal during these tests. Internal to the KaPA are temperature sensor, gate current and gate-voltage telemetry measurements. External to the KaPA are other temperature sensors, as well as RF power detectors monitoring both input and output RF power. From these, RF gain can be deduced. At the same time, the SDST collects internal and external diagnostic-telemetry signals, which can isolate (to the SDST RF output, the intervening telecom-system components, or the KaPA) the location of any potential degradation of performance. This ability to isolate problems was part of the DS1 technology-validation plan, as SDST and KaPA came from different industrial partners.

Besides characterizing the KaPA operation and link during the primary mission, DS1 has subsequently provided Ka-band modulated and unmodulated signals for DSN performance-verification, improved ground-system design and network-component upgrades to operational use of Ka-band. In the 3 years since launch, the lifetime of the KaPA has been proven through hundreds of hours of operation.

4.3 Beacon Monitor Operations Experiment

4.3.1 Beacon System Concept Description

Beacon-monitor technology allows a spacecraft to report its status without transmitting telemetry on the downlink. The status provides information the ground system requires to intervene by scheduling a telemetry-downlink or command-uplink session.

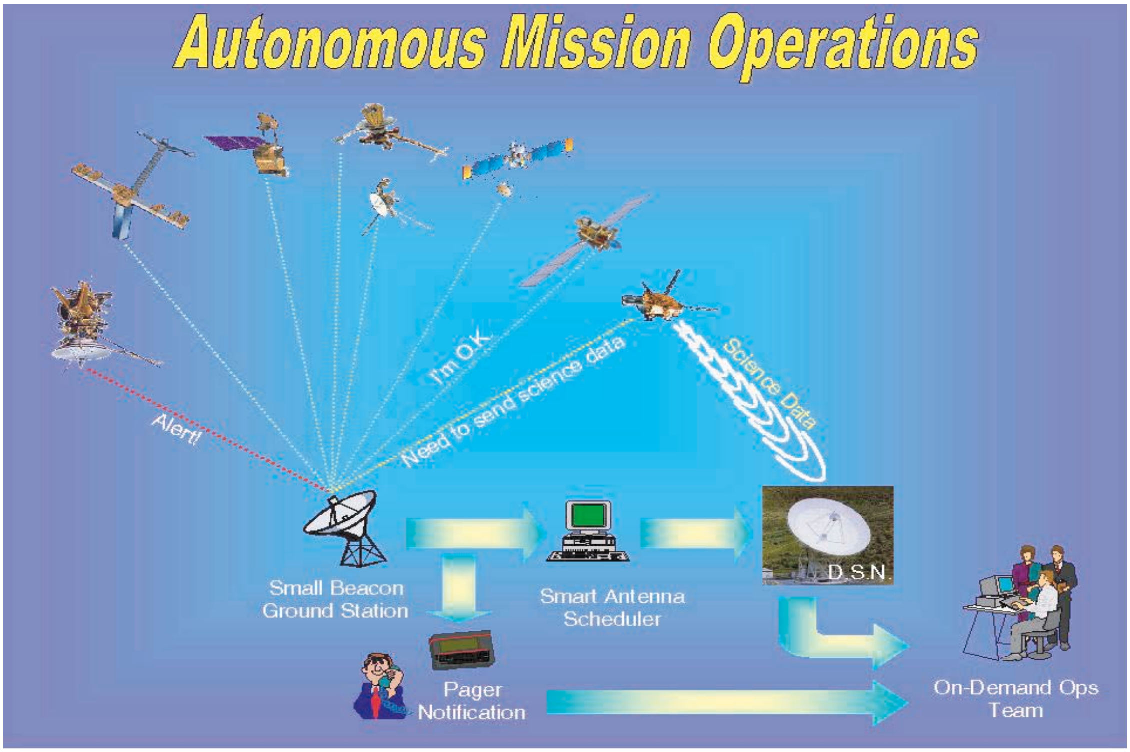

Fig. 4-3. Beacon monitoring system elements building on DS1 Beacon Monitor Operations Experiment demonstration concepts.

The main appeal of a beacon system is that, when DSN resources are scarce and spread out among many missions, it's cheaper to build and deploy small stations at different locations with tone-detection capability only. Noncoherent tone doesn't require phase-locked receivers, and detection is possible at a lower total-received power than for telemetry at even low-bit rates. Figure 4-3 shows future beacon monitoring-system elements.

The onboard monitoring system for a typical, future beacon-equipped spacecraft would consist of flight software and part of the telecom system [2], and be responsible for:

- Analyzing the engineering data to determine spacecraft health
- Reducing health status to one of a few (perhaps the four implemented in DS1) monitoring states, also known as beacon states or tone states
- Mapping the current monitoring state into an appropriate monitoring signal
- Transmitting the monitoring signal to the ground.

Future system-ground components would include a new set of monitor stations and a coordination computer. One proposed beacon system has an 8-m antenna at each DSN site. The monitoring system also includes support by project-operations teams and DSN-station scheduling, prediction, and operation systems.

A beacon-monitoring station detects the monitoring signal,[5] using the schedule and predictions from the coordination computer, and then sends the result back to the computer. The computer interprets the beacon message based on rules established by the project. It maintains a monitoring schedule for all spacecraft, and it makes pass requests for a 34-m or 70-m antenna and notifies the project when needed. It also initiates urgent responses when triggered by an urgent message. The DSN prediction systems will provide carrier-frequency and antenna-pointing predictions to the computer, which sends these to the monitor station. The DSN is responsible for scheduling 34-m or 70-m antenna passes in response to the computer requests, as triggered by the detected messages. The future beacon-monitoring system is complemented with the DSN's larger antennas to track spacecraft and send telemetry data to the projects in accordance with the DSN schedule.

When operating in monitoring mode, each spacecraft will maintain a continuous ability to receive commands from the ground. It will transmit its monitoring signal continuously or on a scheduled basis if constrained by spacecraft power or other factors. In the scheduled case, a pre-agreed communication window can be established for monitoring purposes.

During a spacecraft emergency, the DSN will work directly with the project-operations teams as usual, bypassing the coordination computer. When intensive interaction is needed between the spacecraft and the ground, the monitoring mode can be terminated by a ground command, or by the onboard computer. If onboard fault-protection software detects a condition requiring rapid ground intervention, the spacecraft will revert to safe mode and transmit low-rate telemetry to the ground.

4.3.2 The DS1 Beacon Monitor Operations Experiment

The DS1 Beacon Monitor Operations Experiment (BMOX) new technology consists of flight software that controls existing SDST subcarrier-frequency modes and includes two functions:

- Problem- or condition-detection and tone transmission—instead of routinely sending spacecraft-health data, the spacecraft evaluates its own state and transmits one of four beacon tones that reveal how urgent it is to send high-rate health data
- Data summarization—when telemetry tracking is required, it creates and transmits "intelligent" summaries of onboard conditions to the ground instead of bulk-telemetry data.

The tone-generation function was validated first. Stored-command sequences controlled the SDST directly, producing over a period of several hours, an unmodulated carrier, and a suppressed carrier that was successively modulated by subcarrier frequencies of 20, 25, 30, and 35 kHz. The subcarrier frequencies served as the tones. In a fully functional beacon system, the particular tone would indicate a "nominal," "interesting," "important," or "urgent" condition.

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[5] The beacon mode in the future system could use M-ary FSK (phase-shift keying in which the modulated carrier can assume any of 'm' values, thus providing 2^m unique messages) with noncoherent detection, in contrast to phase modulation using coherent receivers for deep-space telemetry.

The spacecraft-technology validation's tone-transmission also checked the station-predict function, the BMOX station-control software, and the station's ability to detect weak X- and Ka-band tone-modulated carriers. Subsequently, the BMOX flight software, not just a stored sequence, controlled which SDST subcarrier would be produced. In early 2000, weekly tone-transmission tests were sequenced to complete the station BMOX-operations automation.

The data-summarization function matured later in both the prime and the extended mission. Tone-transmission capability was first used operationally in mid-2000 as part of the overall spacecraft-pointing algorithm[6] and IPS-thrusting operation. Transmission of tones in this phase is not controlled by the BMOX software but by another part of the flight software. The tones' purpose at this time is to convey only one piece of information: the pointing algorithm's star-lock history.

4.4 Telecom System Mass and Input Power

For comparison with similar functions in other spacecraft, Table 4-1 shows values of mass and spacecraft power for major elements of the DS1 telecom hardware discussed in Sections 3 and 4. The mass values and some power values come from the technology validation reports [6] and pre-launch project reports (JPL internal documents). Where available, the power values are taken from in-flight engineering telemetry. The telemetry confirms there has been negligible drift in power usage by the receiver, exciters, or power amplifiers from 1998 to 2001.

Table 4-1. DS1 telecom system mass and power summary.

System Unit	Input Power (W[a])	Mass (kg)	Dimensions (cm)
Receiver	11.8		
X-band exciter, 2-way	1.8		
X-band exciter, 1-way	2.3		
Ka-band exciter	3.9		
SDST		3.1	
XPA	52.5	1.6	
KAPA	16.9	0.7	14.2 × 15.2
HGA		1.2	
KHA		0.8	
LGAX		0.4	
LGAZ+		0.4	
LGAZ–		0.4	

[a]Based on in-flight telemetry data

[6] The ACS pointing algorithm developed after the SRU failure depends on the software maintaining lock to a reference star. A "tone detection" sequence that is activated during selected tracking passes will cause a 35-kHz frequency to modulate the downlink carrier if star-lock status has remained normal. It will modulate the downlink with a 20-kHz frequency if star-lock has been lost for more than a preset time—currently 1.5 hours.

Section 5

Telecom Ground System Description

The DSN* [10] is the ground system that transmits to and receives data from the DS1 spacecraft and many other deep-space missions. The DSN is an international network of ground stations (antennas, transmitters, receivers, and associated systems) that operates intensively at S- and X-band, and with Ka-band being developed. The DSN supports interplanetary-spacecraft missions and radio- and radar-astronomy observations for the exploration of the solar system and beyond. The DSN consists of three deep-space communications facilities placed approximately 120 deg apart around the world: at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia.

This section includes brief descriptions and functional block diagrams of DSN systems that provide carrier tracking, radiometric data (Doppler and ranging) collection, command uplinking, and telemetry reception and decoding for DS1.

Specific DSN numerical parameters for DS1 are defined in the PR/TSA [8] and the Network Operations Plan [11].

5.1 Uplink and Downlink Carrier Operation

DSN stations are grouped by antenna size (26 m, 34 m, and 70 m), and for the 34-m antennas by type—BWG (beam-waveguide) or HEF (high-efficiency). DS1 has been tracked by 70-m, 34-m HEF, and 34-m-BWG stations. The *DSMS Telecommunications Link Design Handbook* [12] includes functional capability descriptions of each antenna size and type, for the purpose of modeling link capability between a spacecraft and that station type. These 70- and 34-m stations all receive X-band downlinks. The 34-m stations have had X-band uplink capability through the DS1 mission. The 70-m stations were X-band downlink only at DS1 launch; by November 2001, all three will have X-band uplink capability also.

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

5.1.1 The 34-Meter Station (DSS-25)

This section describes the system functions at Deep Space Station 25 (DSS-25), the 34-m-BWG station at Goldstone. This operational station supports the DS1 X-band uplink and downlink, as well as Ka-band downlink.[1]

Figure 5-1 is the DSS-25 antenna and microwave section functional diagram. Although these elements are representative, [12] provides specific figures for each type of station and indicates the sometimes significant differences among stations of a particular type.

The RF output from the 4-kW X-band transmitter goes through the X-band diplexer, then through an orthomode junction and polarizer to the X-band feed. For DS1, the transmitter is set to RCP except when the spacecraft LGAZ– is scheduled to be in view of Earth. The X-band uplink continues to the subreflector via an X-band/Ka-band dichroic plate, if simultaneous Ka-band is required. From the subreflector, the X-band uplink is focused to the 34-m main reflector, which is oriented in the direction of the spacecraft during the active track.

The X-band downlink signal from the spacecraft is collected by the 34-m main reflector, then is focused by the subreflector to the X-band feed (again via the X-band/Ka-band dichroic when there is also a Ka-band downlink from the spacecraft). The polarizer is set for RCP reception for DS1 except when LGAZ– is scheduled. The orthomode junction is the part of the antenna feed that combines or separates LCP and RCP signals. From the feed the X-band RF signal goes to the X-band maser preamplifier. After low-noise amplification, the downlink is frequency down-converted to a 300-MHz intermediate frequency (IF) for input to the Block V Receiver (BVR).

The Ka-band downlink also is collected by the 34-m main reflector and focused by the subreflector. It passes through the dichroic plate to separate it from the X-band downlink signal path, on its way to the Ka-band feed. DSS-25 is equipped only for RCP at Ka-band (and the DS1 KHA is RCP). The Ka-band preamplifier is a high-electron-mobility transistor (HEMT). Like the X-band downlink, after low-noise pre-amplification, Ka-band downlink is frequency down-converted for input to the BVR.

5.1.2 The 70-Meter Stations (DSS-14 and DSS-43)

The 70-m stations provide S-band uplink and downlink for those missions that require those frequencies. For DS1, the stations' X-band uplink and downlink are used. Figure 5-2 (from [12], module 101) shows the antenna and microwave sections of DSS-14 and DSS-43 as they have existed since the installation of the X-band uplink in 2000.[2]

The 20-kW X-band transmitter output goes through a polarizer and a diplexing junction to the X-band feed. From there, it passes through an S-band/X-band dichroic reflector on its way to the subreflector and the main 70-m reflector that sends the uplink on its way to the spacecraft.

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[1] Of the operational 70-m and 34-m-BWG stations, only DSS-25 has had Ka-band-downlink capability throughout the DS1 mission.

[2] The third 70-m station, DSS-63 at Madrid, will have X-band uplink installed by November 2001. DSS-63 has also supported DS1, but with a concurrently-scheduled 34-m station when an uplink was required.

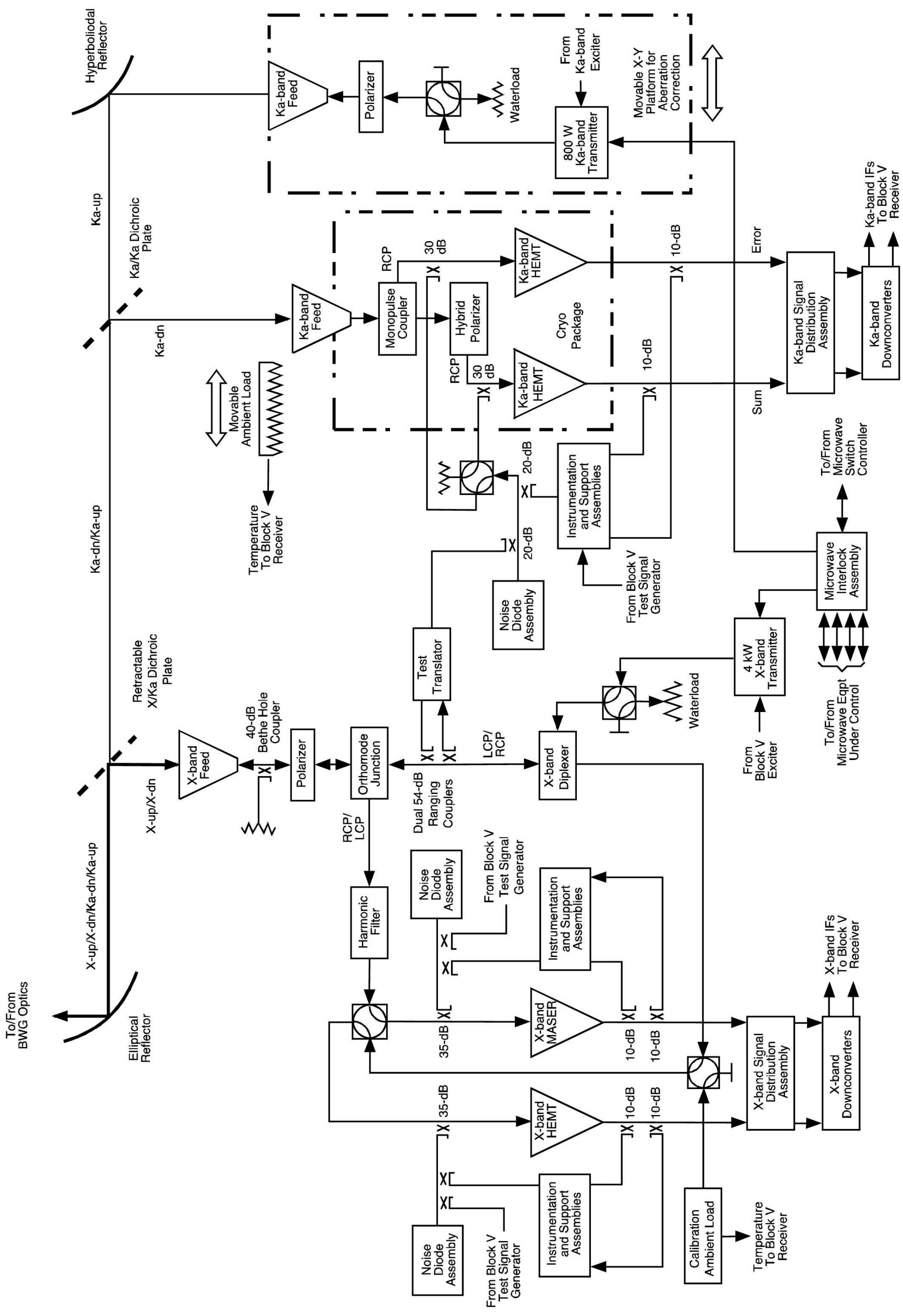

Fig. 5-1. DSS-25 functional diagram (X-band uplink/downlink, Ka-band downlink).

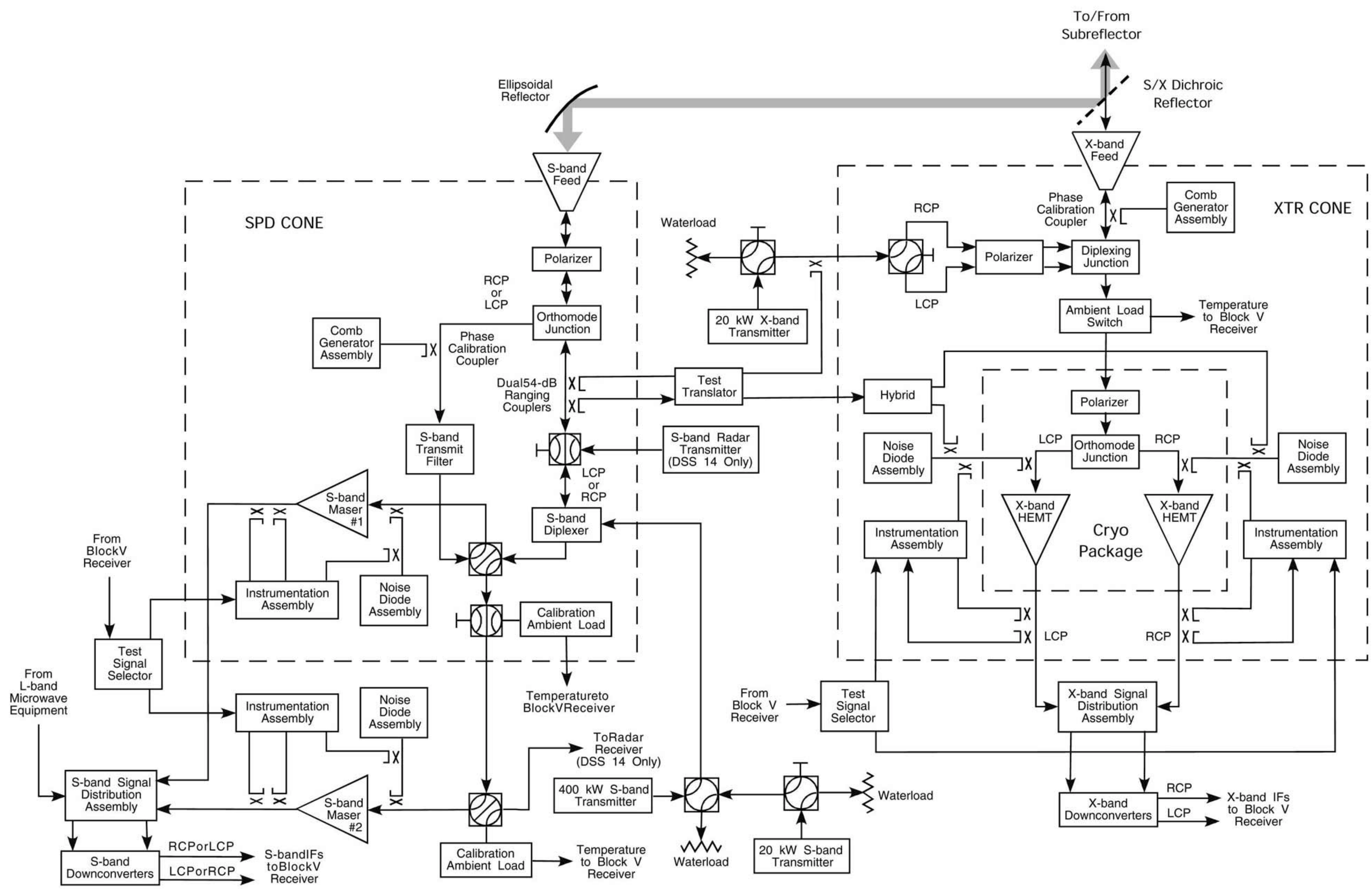

Fig. 5-2. DSS-14 and DSS-43 functional-block diagram (X-band uplink and downlink).

The X-band downlink from the main reflector is focused by the subreflector and passes through the dichroic reflector to separate it from the S-band signal path. From the diplexing junction, the X-band downlink goes to a polarizer that selects the RCP output for all DS1 antenna except LGAZ–. The X-band downlink from the X-band HEMT preamplifier is frequency-down-converted for input to the BVR.

5.2 Radiometric Data (Doppler and Ranging)

The DS1 uplink-and-downlink carriers provide a means of measuring the station-to-spacecraft velocity as a Doppler shift. In addition, ranging modulation applied to the uplink is turned around by the SDST to modulate the downlink to provide a means of measuring the station-to-spacecraft distance. Together, Doppler-and-ranging data provide radio navigation inputs to the project. Radio navigation and optical navigation have both been mainstays for DS1 orbit determination. Radio navigation also played a part in the technology validation of “auto-nav.”

Figure 5-3 and 5-4 (from [13], document 810-5, Rev. D) show the metric-data assembly (MDA) and the sequential-ranging assembly (SRA).[3]

Figure 5-5 (from [11], the Network Operations Plan [NOP] for DS1) shows the ground systems involved in Doppler and ranging-data processing for DS1.

In addition to the antenna, BVR, and transmitter already discussed, the equipment at the Goldstone, Madrid, or Canberra Deep Space Communications Complex (DSCC) includes the MDA and SRA.

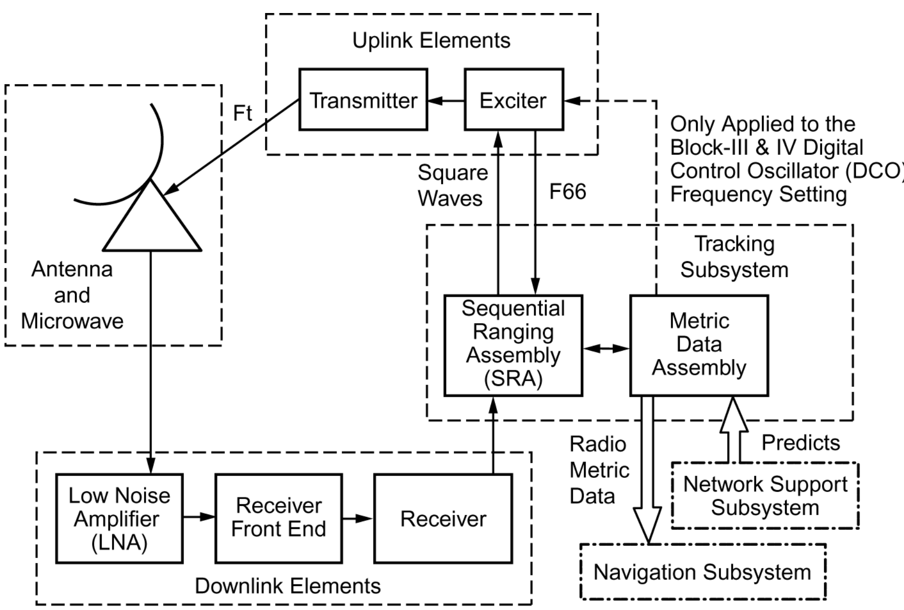

Fig. 5-3. DSN ranging system (from [13], 810-5, Rev. D, module TRK-30).

[3] DSN/Project-interface specifications are now defined in document 810-005 (Rev. E) [12]. However, in some cases, the older diagrams in document 810-5 (Rev. D) [13] better represent the DSN systems as they were configured for DS1. This article distinguishes between the newer and older sources of station information.

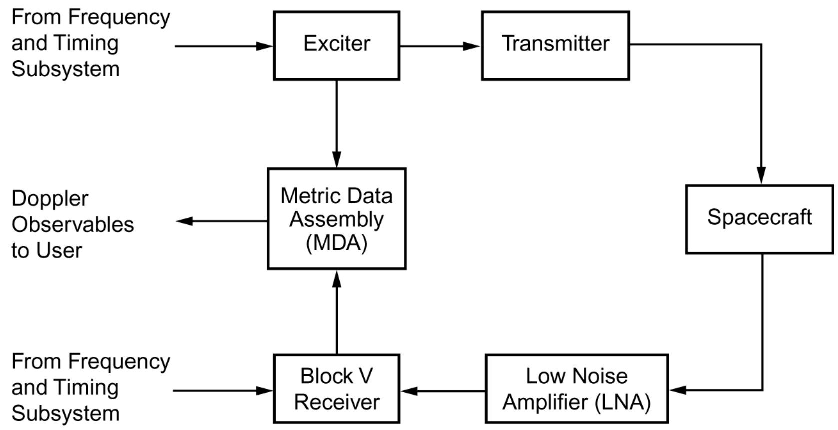

Fig. 5-4. DSN Doppler system (from [13], 810-5, Rev. D, module TRK-20).

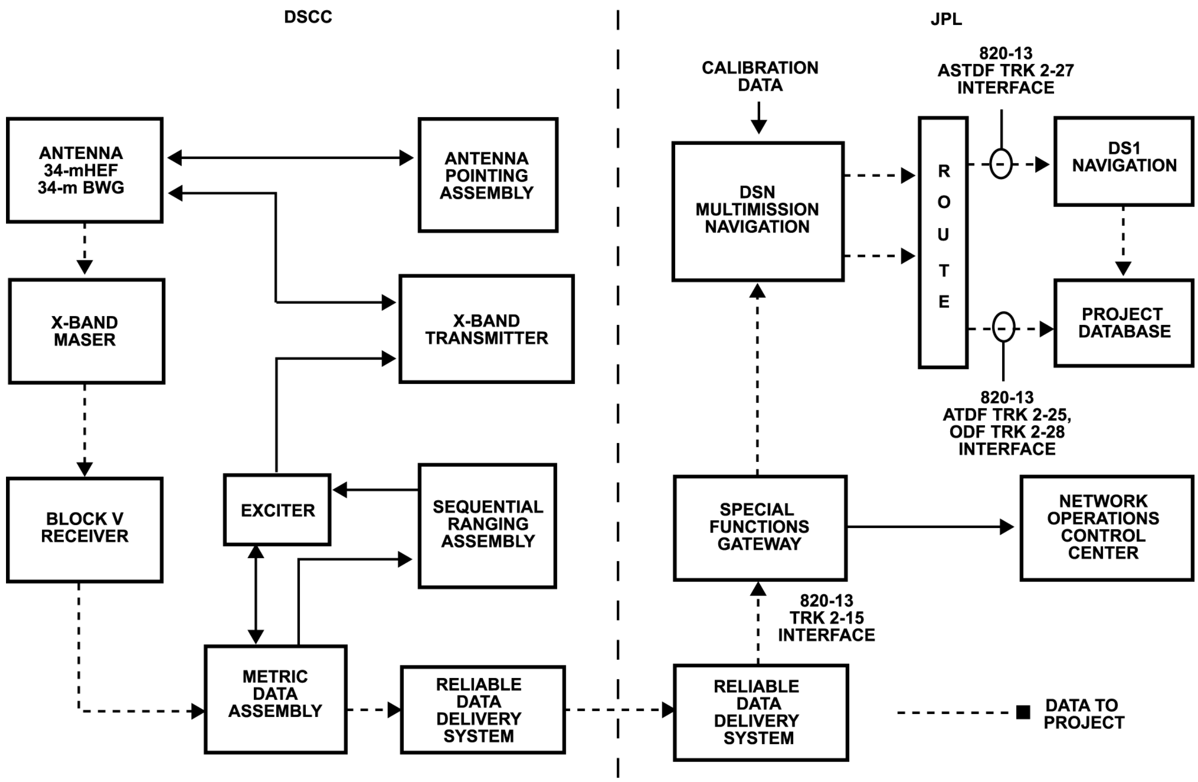

Fig. 5-5. DSN end-to-end radiometric data-flow diagram (from 871-010-030).

5.2.1 Ground Systems for Doppler Data

The BVR provides downlink phase to the MDA, for Doppler measurement. When the SDST in the spacecraft is locked to an uplink carrier, the MDA compares the downlink phase to the uplink phase that was transmitted a RTLT earlier, for two-way Doppler. The Doppler measurements establish the spacecraft-station velocity as a function of time and can be compared with the expected or modeled velocity. The Doppler-sample rate for DS1 is normally 10 samples/s. Doppler-integration times have sometimes been made longer to counter weak downlink levels.

5.2.2 Ground Systems for Ranging Data

For the DS1 mission, the uplink-ranging data sent to the spacecraft and the ranging data demodulated from the downlink carrier are both processed in the SRA. The name refers to the sequence of square-wave frequencies sent to the spacecraft, with the highest frequency ("clock") providing fine resolution in range. Square-wave frequencies at successive submultiples of the clock-resolve ambiguity.[4] As defined in the NOP, to accommodate the lower-link margins in the extended mission, DS1 uses a 300-s integration time for the clock component and 20-s integration time for the lower-frequency components. Standard DS1 ranging uses components 4 through 20 [11] for ambiguity resolution.

5.2.3 Ground Processing of Navigation Data

At JPL, the Radiometric Data Conditioning Group, part of the Multimission Navigation function, processes and delivers the Doppler and ranging data to DS1 project navigation. DS1 navigation may do further processing of the delivered Doppler and ranging files in the trajectory-determination process, for example, weighting[5] the values of data from specific passes relative to other passes). In addition to providing information to the project to conduct the mission, the radio-navigation data are used to generate P-files for delivery back to the DSN, for use in creating the frequency and pointing predicts for subsequent tracking passes. Frequency predicts are input to the BVR to assist in locking the receiver to expected periods of one-way, two-way, or three-way data. Pointing predicts are used to drive the station antenna in elevation and azimuth angle during the pass. Pointing predicts are supplemented by several tables that are specific to the station type, location, and the general declination of the spacecraft. These supplementary tables include corrections for atmospheric refraction as a function of elevation angle and azimuth as well as for deformation of the antenna structures (and thus, changes in the beam direction) as a function of elevation angle.

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[4] The process of ranging involves correlation between the transmitted and received waveforms. The correlation results in an infinity of solutions, separated one wavelength apart, creating the ambiguity. The ranging system resolves (eliminates) the ambiguity by successively correlating a series of waveforms, each one having a wavelength twice as long as the previous, until the spacecraft's location is unambigous as determined by means other than the current range measurement.

[5] Weighting is an art in navigation-orbit determination, in which the available datasets (or even individual-ranging points) are assigned relative value (importance) relative to other datasets. Weighting may involve such factors as the amount of scatter between successive points, the agreement between the range and Doppler points within a pass, and how well the points from one pass "fit" into the solution model, as determined from previous passes. Orbit determination for DS1 has been a challenging process because of the extensive periods of low-level thrusting. The effects of thrusting have to be separated from other small forces, such as solar pressure.

5.3 Command Processing and Radiation

Figure 5-6 (from the NOP, [11]) shows the systems at JPL and the station involved in the commanding process for DS1.

DS1 command files are moved to the station ("staged") in advance of need in a store-and-forward system. The following description is of the systems [13] used during the DS1 mission. At the station, the command-processor assembly (CPA) and the command-modulator assembly (CMA) clock out the command bit stream, modulate the command subcarrier, and provide the subcarrier to the exciter for RF-uplink carrier modulation. Bit rates, the command subcarrier frequency, and the command-modulation index (suppression of the uplink carrier) are controlled through standards and limits (S&L) tables.

At JPL, the DS1 ACE (call sign for project real-time mission controller) operates the multimission command system from a workstation in the DS1 mission-support area (MSA). To begin or end a command session, the ACE requests the station to turn the command modulation on or off, respectively. The ACE selects a command rate, for example 125 bps. The selected rate is associated with one of four values of uplink-carrier suppression by command modulation (or modulation index). The carrier suppression is established by use of one of four calibrated "buffers" in the station's CMA. The CMA produces the command subcarrier, which has a nominal frequency of 16000.2 Hz to match the subcarrier tracking loop best-lock frequency in the DS1 SDST. The CMA also modulates the command-bit waveform onto the subcarrier.

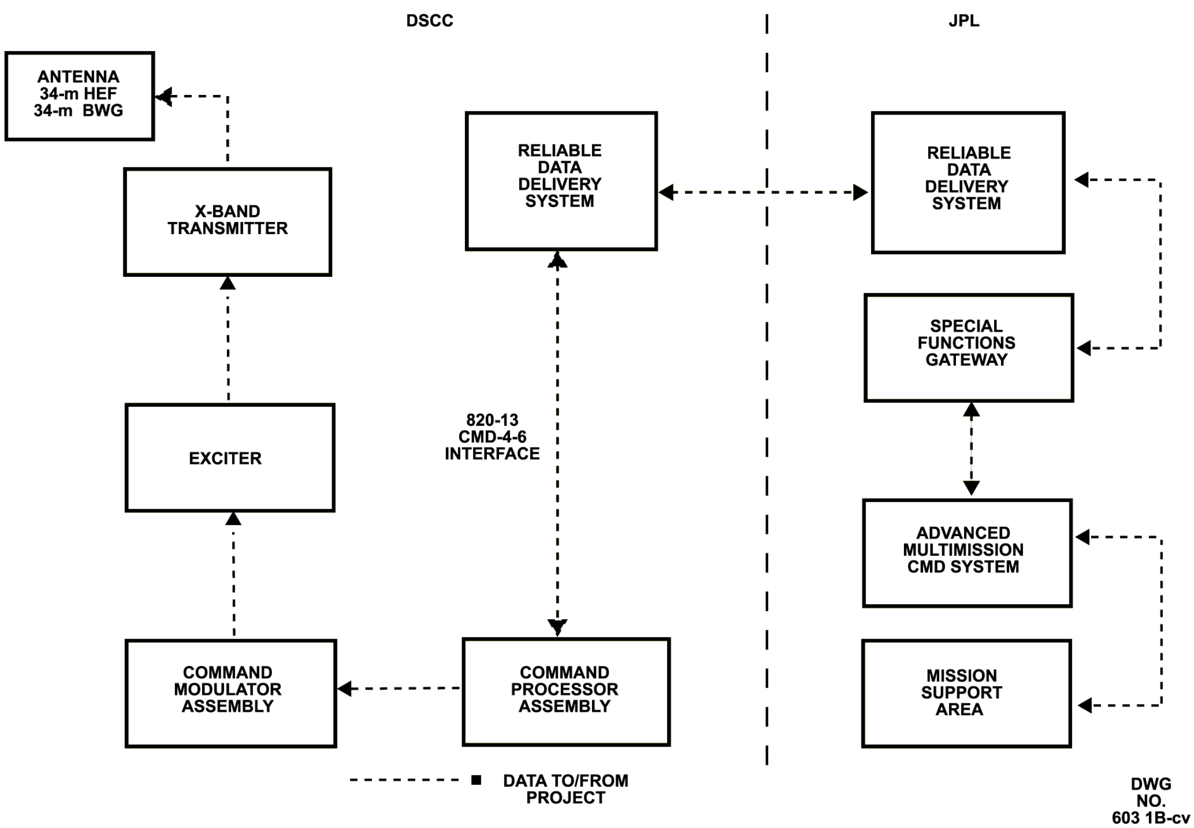

Fig. 5-6. DSN end-to-end command data-flow diagram (from 871-010-030).

The Reliable Data Delivery System (now called the Reliable Network System or RNS) transfers the command files to the station in the staging process, as well as the ACE directives for radiation of the staged commands. At the station, the Command Processor Assembly performs the digital processing to create the command-bit stream from the command files and the activation signal. Experience with critical-command timing, as in the "HGA Activities" described in Section 7, shows that an ACE is able to activate command transmission within 2 s of the nominal time.

5.4 Telemetry Demodulation, Decoding, Synchronization, and Display

The Telemetry System performs three main functions: data acquisition, data conditioning and transmission to projects, and telemetry-system validation.

Figure 5-7 shows the station equipment involved in DS1 telemetry-demodulation and decoding.

Each of the two redundant BVRs has phase-locked loops for receiving (locking to) the carrier, the telemetry subcarrier, and the telemetry-symbol stream. DS1 generates a 375-kHz subcarrier for telemetry bit rates of 2100 bps or greater, and a 25-kHz subcarrier for bit rates lower than 2100 bps. DS1 X-band carrier-modulation index values range from 40 deg for the lowest data rate (10 bps) to 72 deg for the highest (19,908 bps).

The BVR delivers telemetry symbols to the maximum-likelihood convolutional decoder (MCD). For spacecraft with (7,1/2) coding, either MCD2 or MCD3 may be used. The (15,1/6) convolutional code normally used by DS1 requires the use of the MCD3. An MCD/FSS (Frame Synchronizer System) pair make up a telemetry-channel assembly (TCA). The telemetry-group controller (TGC) controls the operation of TCA1 (containing the MCD3) and TCA2 (containing an MCD2).

The MCD outputs decoded telemetry bits to the frame-synchronizer (FS) subsystem. After the MCD declares lock, the FSS requires recognition of a minimum of two successive frame-sync words to output ("flow") telemetry to the project. Validation requires recognition of a third sync word. The number of sync-word-allowable bit miscompares for recognition and validation can be set in the software.

Figure 5-8 (from the NOP, [11]) shows the end-to-end telemetry data flow from the station to the project analysts in the MSA. The Advanced Multimission Operations System (AMMOS) processes telemetry in both near-real time (delays up to one minute) and in nonreal time (producing data records that are as complete as possible, but with a delivery time guaranteed within 2 hours of the end of track). The nonreal-time version includes retransmission of data lost between the station and JPL and replays from the central data recorder (CDR) as necessary.

AMMOS telemetry processing at JPL includes "channelizing" the data from the packets received, ordering the telemetry data that may have been transmitted in real time or from spacecraft storage, and time-tagging the data either by Earth-received time (ERT) or spacecraft-event time (SCET).

Station configuration and performance ("monitor") data are output by the Link Monitor and Control (LMC), or the newer Network Monitor and Control (NMC) at the station. Monitor

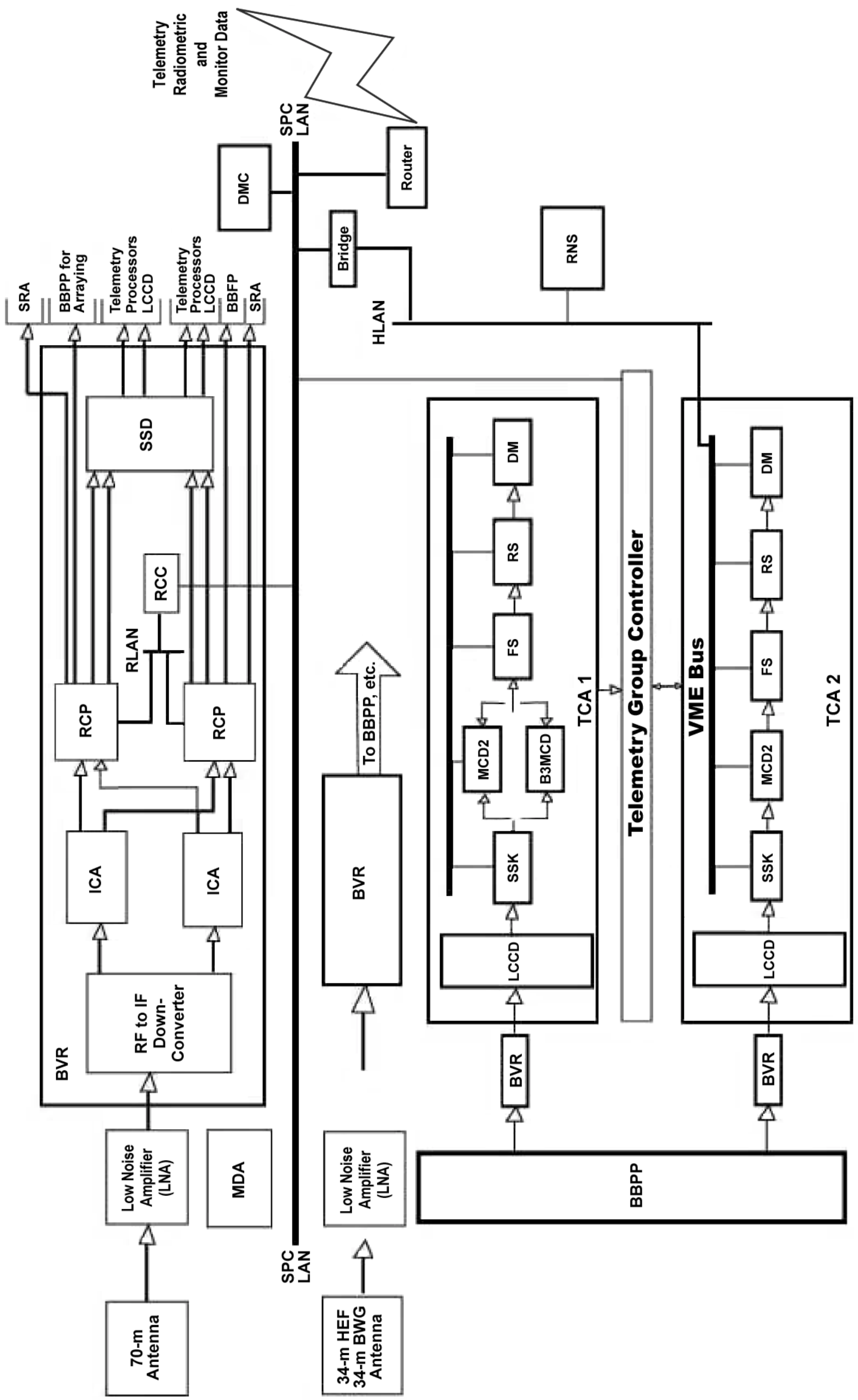

Fig. 5-7. DSN demodulation and production of telemetry data (from 871-010-030).

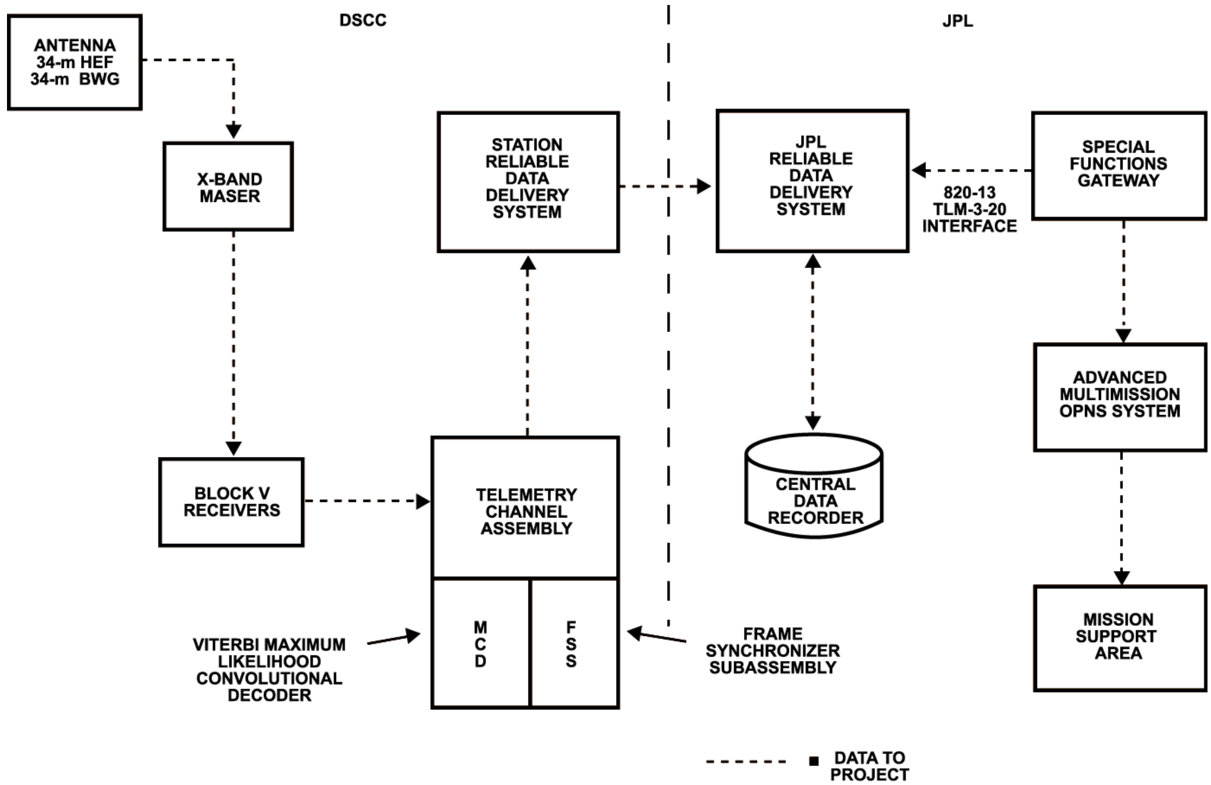

Fig. 5-8. DSN end-to-end telemetry-data-flow diagram (from 871-010-030).

data are channelized similarly to telemetry data and can be displayed or queried for telecom analysis. Monitor data are available only in monitor-sample time (MST), which is analogous to ERT for telemetry.

In the MSA, the near-real-time data are “broadcast” to workstations, which can display them in the form of DMD (Data Monitor and Display) pages. Pages may be in list form, plots, or specially formatted “fixed” pages. Also, at their workstations, the DS1 analysts can query either the near-real-time or the nonreal-time data. The query output can be displayed as tabulations or plots on the screen, routed to a printer, or saved as a file for further processing.

Section 6

Telecom Link Performance

The DS1* communication-link margins are calculated using statistical techniques to establish expected values from the mean and variance, and a further indication of variability from the tolerances and shape (uniform, Gaussian, etc.) [14]. In many cases, link models (such as the LGAX antenna pattern, and the interaction of telemetry-and-ranging modulation in the SDST downlink) were modified from theory or early measurements by additional or iterative analysis of prelaunch measurements.

The three DS1 link functions are command, telemetry, and ranging. Each has a minimum signal-to-noise ratio (called the threshold) at which the quality of the link meets a project-defined criterion.

Link performance is book-kept using a design-control table. In-flight DS1 operations are based on a criterion of positive-link margin under the following conditions: (a) command: mean minus three standard deviations (3σ), (b) telemetry: mean minus 2σ, and (c) ranging: mean minus 2σ. The command link does not have error-correcting coding, so data-stream bits are the same as channel symbols. The telemetry link has concatenated Reed-Solomon and convolutional coding.[1] The parameter σ (spelled out as sigma) in the DCT refers to the standard deviation of the command Eb/No (bit energy to noise-spectral-density ratio), the telemetry Es/No

[1] The DS1 telemetry-transfer frame is a fixed-length data-transfer structure. Details come from the DS1 PR/TSA [8] and Telemetry Dictionary [16]. The telemetry frame is created and Reed-Solomon (RS) encoded in-flight software using a conventional Berlekamp code with an interleave depth of 5. The code is shortened from the standard RS (255,223) code to an RS (252,220) code using 120 bits of virtual-zero fill (not transmitted from the spacecraft) that is used by the decode process to fill out the code block to the standard. This results in an RS code block (transmitted frame) with a total length of 10080 bits: 8800 bits of data and 1280 bits of RS check symbols. Each code block is preceded with a 32-bit synchronization marker, to aid the station in finding the frame boundaries, making up a total 10112-bit structure commonly called the "transfer frame." The sync marker is not included in the RS encoding or decoding processes. For DS1, the SDST encodes the data-stream of 10112-bit frames using either of two selectable-coding formats: K=15, Rate 1/6 or K=7, Rate 1/2.

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

(symbol energy to noise-spectral-density ratio), or the downlink ranging Pr/No (ranging power to noise-spectral-density ratio)[2]. The quantity No is the noise-spectral density; Eb is the energy per bit, Es is the energy per symbol, and Pr is the ranging power.

Tables 6-1, 6-2, and 6-3 design-control tables (DCT) contain predictions of DS1 telecom performance, generated by a software tool, the Telecom Forecaster Predictor (TFP). TFP is a multimission tool for link-performance prediction built upon Matlab [15]. DS1 TFP uses standard models for station parameters (the same for each project's TFP) adapted to include DS1 spacecraft models.

The three DCTs are all for a specific arbitrary instant in time, 2000-173/16:00 UTC (9 a.m. Pacific daylight time, June 21, 2000). The DS1 spacecraft operates with the 70-m DSS-14 antenna at Goldstone. The spacecraft is configured for X-band uplink and downlink on the HGA. The command rate is 2000 bps, at an uplink-modulation index of 1.2 rad. The ranging modulation also suppresses the uplink, at a value of 3 dB. The downlink rate is 3150 bps, at a modulation index of 65.8 deg. The ranging also phase-modulates the downlink, at an index of 0.3 rad. The HGA is presumed to have its boresight misaligned from Earth by 2.5 deg.

TFP shows the time variation of link performance either as tabulations (columns of numbers to be read into a spreadsheet for formatting and printing) or as plot images for viewing or printing.

Performance of command and telemetry during the entire DSS-14 pass on June 21, 2000 is summarized in the two pairs of plots that follow the three DCTs. The plots were created from the same run that produced the three DCTs. All plots contain values predicted once every 20 min., starting at the DCT time of 16:00 UTC and continuing to 04:00 UTC the next day. Quantities plotted for illustration are the mean values of the parameters.

The first plot-pair shows the downlink-ranging mean Pr/No and its threshold of –10 dB at the top and the uplink command mean Eb/No and its threshold of +9.6 dB at the bottom. The second plot-pair shows the station-elevation angle at the top and the downlink-telemetry mean Es/No with its threshold of –7.5 dB at the bottom.[3] Figure 6-1 and 6-2 display, respectively, the downlink Pr/No and uplink Eb/No; and station-elevation angle, and downlink-telemetry symbol SNR.

[2] The ranging DCT defines mean and variance for Pr/No, as a bottom-line telecom-analysis quantity that can be compared against a like-named channel in the station-monitor data. Beyond this, navigation also defines a ranging "sigma" (computed as a function of Pr/No, but which is not included in DS1 DCTs) that is a prediction of the ranging-measurement scatter.

[3] DS1 flight-team link analysis does not receive monitor data from the station indicating the Reed-Solomon decoding performance or the frame-synchronization performance. The Block 5 receiver (BVR) outputs a measure of Es/No, and the maximum-likelihood convolutional decoder (MCD) outputs a measure of Eb/No. The DCTs in this section, accordingly, express predicted-performance relative to thresholds that are in terms of Es/No or Eb/No.

Table 6-1. DS1 uplink (command and ranging) DCT.

Produced by DS1 V5.1 12/16/1999					
Predict	2000-173T16:00:00 UTC				
Up- /downlink	Two-way				
RF band	X:X				
Telecom link	DSS-14-HighGain. ConfigA-DSS-14				
COMMAND UPLINK PARAMETER INPUTS					
Cmd data rate	2000.0000 bps				
Cmd mod index	1.20 rad				
Cmd rngmod index	44.9 deg				
Operations mode	Nominal				
Mission phase	Launch phase				
DSN site	Gold-Gold				
DSN elevation	In view				
Weather/CD	25				
Attitude pointing	EarthPointed				
EXTERNAL DATA					
Range		(km)	3.0816e+08		
Range		(AU)	2.0599e+00		
One-way light time (OWLT)		(hh:mm:ss)	00:17:07		
Station elevation(s)		(deg)	[14.41]		
DOFF: HGA, KHA		(deg)	2.50	2.50	
DOFF: LGA1, LGA2, LGA3		(deg)	2.50	92.50	87.50
Clk: HGA, KHA		(deg)	159.49	0.00	
Clk: LGA1, LGA2, LGA3		(deg)	159.49	0.00	0.00
Added s/c ant pnt offset		(deg)	2.5		
DSN site considered:	DSS-14/DSS-14				
At time:	0.00	hours after the start time			

(Continued on next page)

Table 6-1. DS1 uplink (command and ranging) DCT (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. Total transmitter power	dBm	73.01	0.00	–1.00	72.68	0.0556
2. Xmitter waveguide loss	dB	–0.41	0.05	–0.05	–0.41	0.0004
3. DSN antenna gain	dBi	72.45	0.20	–0.20	72.45	0.0133
4. Antenna pointing loss	dB	–0.10	0.10	–0.10	–0.10	0.0017
5. EIRP (1 + 2 + 3 + 4)	dBm	144.62	0.80	–0.80	144.62	0.0710
PATH PARAMETERS						
6. Space loss	dB	–279.33	0.00	0.00	–279.33	0.0000
7. Atmospheric attenuation	dB	–0.14	0.00	0.00	–0.14	0.0000
RECEIVER PARAMETERS						
8. Polarization loss	dB	–0.03	0.10	–0.10	–0.03	0.0033
9. S/C ant pointing control loss	dB	–0.30	0.20	–0.20	–0.30	0.0133
10. Deg-off-boresight (DOFF) loss	dB	–0.44	0.43	–0.48	–0.47	0.0691
11. S/C antenna gain (at boresight)	dBi	20.10	0.50	–0.50	20.10	0.0417
12. Lumped circuit loss	dB	–1.79	0.30	–0.30	–1.79	0.0300
TOTAL POWER SUMMARY						
13. Tot rcvd pwr (5 + 6 + 7 + 8 + 9 + 10 + 11 +12)	dBm	–117.34	–1.43	1.43	–117.34	0.2284
14. Noise spectral density	dBm/Hz	–172.22	–0.70	0.66	–172.23	0.0779
15. System noise temperature	K	434.75	–65.08	71.69	436.95	779.9427
16. Received Pt/No (13–14)	dB-Hz	54.89	1.66	–1.66	54.89	0.3063
17. Required Pt/No	dB-Hz	50.60	0.00	0.00	50.60	0.0000
18. Pt/No margin (16–17)	dB	4.29	1.66	–1.66	4.29	0.3063
19. Pt/No margin sigma	dB	0.00	0.00	0.00	0.55	0.0000
20. Pt/No margin-3 sigma (18–3*19)	dB	0.00	0.00	0.00	2.63	0.0000

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Table 6-1. DS1 uplink (command and ranging) DCT (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
CARRIER PERFORMANCE						
21. Recovered Pt/No (16 + [AGC+BPF])	dB-Hz	54.89	1.66	–1.66	54.89	0.3063
22. Command carrier suppression	dB	–3.46	0.20	–0.20	–3.46	0.0067
23. Ranging carrier suppression	dB	–3.00	0.10	–0.10	–3.00	0.0017
24. Carrier power (AGC)	dBm	–123.80	–1.46	1.46	–123.80	0.2367
25. Received Pc/No (21 + 22 + 23)	dB-Hz	48.43	1.68	–1.68	48.43	0.3146
26. Carrier loop noise BW	dB-Hz	20.16	–0.20	0.15	20.13	0.0102
27. Carrier loop SNR (CNR) (25–26)	dB	28.30	1.71	–1.71	28.30	0.3248
28. Recommended CNR	dB	12.00	0.00	0.00	12.00	0.0000
29. Carrier loop SNR margin (27–28)	dB	16.30	1.71	–1.71	16.30	0.3248
CHANNEL PERFORMANCE						
30. Command data suppression	dB	–3.04	0.17	–0.18	–3.04	0.0051
31. Ranging data suppression	dB	–3.00	0.10	–0.10	–3.00	0.0017
32. Received Pd/No (21 + 30 + 31)	dB-Hz	48.85	1.68	–1.68	48.85	0.3130
33. 3-sigma Pd/No (32–3*sqrt [32var])	dB-Hz	47.17	0.00	0.00	47.17	0.0000
34. Data rate (dB-Hz)	dB-Hz	33.01	0.00	0.00	33.01	0.0000
35. Available Eb/No (32–34)	dB	15.84	1.68	–1.68	15.84	0.3130
36. Implementation loss	dB	1.50	–0.50	0.50	1.50	0.0833
37. Radio loss	dB	0.00	–0.30	0.30	0.00	0.0300
38. Output Eb/No (35–36–37)	dB	14.34	1.96	–1.96	14.34	0.4264
39. Required Eb/No	dB	9.60	0.00	0.00	9.60	0.0000
40. Eb/No margin (38–39)	dB	4.74	1.96	–1.96	4.74	0.4264
41. Eb/No margin sigma	dB	0.00	0.00	0.00	0.65	0.0000
42. Eb/No margin–3sigma (40–3*41)	dB	0.00	0.00	0.00	2.78	0.0000
43. BER (from 38)	none	8.5494e–14				

Table 6-2. DS1 downlink (telemetry and ranging) DCT.

Produced by DS1 V5.1 12/16/1999				
Predict	2000-173T16:00:00 UTC			
Up- /downlink	Two-way			
RF band	X:X			
Diplex mode	N/A			
LNA selection	LNA-1			
Telecom link	DSS-14-HighGain. ConfigA-DSS-14			
TELEMETRY DOWNLINK PARAMETER INPUTS				
Encoding	Reed-Solomon (255,223) concatenated with C.E. (15,1/6)			
Carrier tracking	Residual			
Oscillator	VCO			
Subcarrier mode	Squarewave			
PLL bandwidth	1.00 Hz			
Telemetry usage	Engineering (ENG)—real time			
Telemetry data rate/mod index	3150	bps/ 65.80	deg (38 DN)	
Telemetry rng/DOR mod index	0.30	rads/ off	rad	
Operations mode	Nominal			
Mission phase	Launch phase			
DSN site	Gold-Gold			
DSN elevation	In view			
Weather/CD	25			
Attitude pointing	EarthPointed			
EXTERNAL DATA				
Range	(km)	3.0816e+08		
Range	(AU)	2.0599e+00		
One-way light time (OWLT)	(hh:mm:ss)	00:17:07		
Station elevation(s)	(deg)	[14.41]		
DOFF: HGA, KHA	(deg)	2.50	2.50	
DOFF: LGA1, LGA2, LGA3	(deg)	2.50	92.50	87.50
Clk: HGA, KHA	(deg)	159.49	0.00	
Clk: LGA1, LGA2, LGA3	(deg)	159.49	0.00	0.00
Added s/c Ant pnt offset	(deg)	2.5		
DSN site considered:	DSS-14/DSS-14			
At time:	0.00	hours after the start time		

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Table 6-2. DS1 downlink (telemetry and ranging) DCT (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. S/C transmitter power	dBm	40.97	0.50	–0.50	40.97	0.0417
2. S/C xmit circuit loss	dB	–1.91	0.30	–0.30	–1.91	0.0300
3. S/C antenna gain	dBi	24.60	0.60	–0.60	24.60	0.0600
4. Deg-off-boresight (DOFF) loss	dB	–0.98	0.21	–0.19	–0.97	0.0134
5. S/C pointing control loss	dB	–0.30	0.20	–0.20	–0.30	0.0133
6. EIRP (1 + 2 + 3 + 4 + 5)	dBm	62.39	1.19	–1.19	62.39	0.1584
PATH PARAMETERS						
7. Space loss	dB	–280.73	0.00	0.00	–280.73	0.0000
8. Atmospheric attenuation	dB	–0.14	0.00	0.00	–0.14	0.0000
RECEIVER PARAMETERS						
9. DSN antenna gain	dBi	74.00	0.20	–0.20	74.00	0.0133
10. DSN antenna pnt loss	dB	–0.10	0.10	–0.10	–0.10	0.0033
11. Polarization loss	dB	–0.02	0.10	–0.10	–0.02	0.0033
TOTAL POWER SUMMARY						
12. Tot rcvd pwr (6 + 7 + 8 + 9 + 10 + 11)	dBm	–144.61	–1.27	1.27	–144.61	0.1784
13. SNT (system-noise temperature) at zenith	K	18.39	–2.00	2.00	18.39	0.6667
14. SNT due to elevation	K	5.02	0.00	0.00	5.02	0.0000
15. SNT due to atmosphere	K	8.60	0.00	0.00	8.60	0.0000
16. SNT due to the Sun	K	0.00	0.00	0.00	0.00	0.0000
17. SNT due to other hot bodies	K	0.00	0.00	0.00	0.00	0.0000
18. System noise temperature (13 + 14 + 15 + 16 + 17)	K	32.01	–2.00	2.00	32.01	0.4444
19. Noise spectral density	dBm/Hz	–183.55	–0.28	0.26	–183.56	0.0082
20. Received Pt/No (12–19)	dB-Hz	38.95	1.30	–1.30	38.95	0.1866
21. Required Pt/No	dB-Hz	38.30	0.00	0.00	38.30	0.0000
22. Pt/No margin (20–21)	dB	0.65	1.30	–1.30	0.65	0.1866
23. Pt/No margin sigma	dB	0.00	0.00	0.00	0.43	0.0000
24. Pt/No margin-2sigma (22–2*23)	dB	0.00	0.00	0.00	–0.22	0.0000

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Table 6-2. DS1 downlink (telemetry and ranging) DCT (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
CARRIER PERFORMANCE						
25. Recovered Pt/No (20 + [AGC + BPF])	dB-Hz	38.95	1.30	–1.30	38.95	0.1866
26. Theoretical tlm carrier sup	dB	–7.75	0.56	–0.61	–7.76	0.0570
27. Non-lin SDST tlm carr sup	dB	0.20	0.20	–0.20	0.20	0.0067
28. Total tlm carr sup (26 + 27)	dB	–7.56	–0.76	0.76	–7.56	0.0637
29. Theoretical rng carrier sup	dB	–0.26	0.04	–0.05	–0.26	0.0003
30. Non-lin SDST rng carr sup	dB	–0.54	0.20	–0.20	–0.54	0.0067
31. Total rng carr sup (29 + 30)	dB-Hz	–0.80	–0.25	0.25	–0.80	0.0070
32. DOR carrier suppression	dB	0.00	0.00	0.00	0.00	0.0000
33. Carrier power (AGC) (12 + 28 + 31 + 32)	dBm	–152.97	–1.50	1.50	–152.97	0.2491
34. Received Pc/No (25 + 28 + 31 + 32)	dB-Hz	30.58	1.52	–1.52	30.58	0.2573
35. Carrier loop noise BW	dB-Hz	0.00	0.00	0.00	0.00	0.0000
36. Carrier loop SNR (CNR) (34–35)	dB	30.58	1.52	–1.52	30.58	0.2573
37. Recommended CNR	dB	10.00	0.00	0.00	10.00	0.0000
38. Carrier loop SNR margin (36–37)	dB	20.58	1.52	–1.52	20.58	0.2573
TELEMETRY PERFORMANCE						
39. Theoretical tlm data sup	dB	–0.80	0.11	–0.12	–0.80	0.0023
40. Non-lin SDST tlm data sup	dB	0.00	0.20	–0.20	0.00	0.0067
41. Total tlm data sup (39 + 40)	dB	–0.80	–0.28	0.28	–0.80	0.0090
42. Theoretical rng data sup	dB	–0.26	0.04	–0.05	–0.26	0.0003
43. Non-lin SDST rng data sup	dB	–1.10	0.20	–0.20	–1.10	0.0067
44. Total rng data sup (42 + 43)	dB-Hz	–1.36	–0.25	0.25	–1.36	0.0070
45. DOR data suppression	dB	0.00	0.00	0.00	0.00	0.0000
46. Received Pd/No (25 + 41 + 44 + 45)	dB-Hz	36.79	1.35	–1.35	36.79	0.2025
47. Two sigma Pd/No (46–2*sqrt(46var))	dB-Hz	35.89	0.00	0.00	35.89	0.0000
48. Data rate	dB-Hz	34.98	0.00	0.00	34.98	0.0000
49. Available Eb/No (46–48)	dB	1.80	1.35	–1.35	1.80	0.2025
50. Subcarrier demod loss	dB	0.01	0.00	0.00	0.01	0.0000
51. Symbol sync loss	dB	0.01	0.00	0.00	0.01	0.0000

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Table 6-2. DS1 downlink (telemetry and ranging) DCT (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
52. Radio loss	dB	0.01	–0.00	0.00	0.01	0.0000
53. Output Eb/No (49–50–51–52)	dB	1.78	1.35	–1.35	1.78	0.2025
54. Output SSNR (Es/No)	dB	–6.00	–1.35	1.35	–6.00	0.2025
55. Required Eb/No	dB	0.30	0.00	0.00	0.30	0.0000
56. Eb/No margin (53–55)	dB	1.48	1.35	–1.35	1.48	0.2025
57. Eb/No margin sigma	dB	0.00	0.00	0.00	0.45	0.0000
58. Eb/No margin–2sigma (56–2*57)	dB	0.00	0.00	0.00	0.58	0.0000
59. BER of conv decoder (from 53)	none	1.1063e-05				

Table 6-3. DS1 ranging performance (uplink and downlink) DCT.

Produced by DS1 V5.1 12/16/1999			
Predict	2000-173T16:00:00 UTC		
Up- /downlink	Two-way		
RF band	X:X		
Diplex mode	N/A		
LNA selection	LNA-1		
Telecom link	DSS-14-HighGain. ConfigA-DSS-14		
COMMAND UPLINK PARAMETER INPUTS			
Cmd data rate	2000.0 bps		
Cmd mod index	1.20 rad		
Cmd rngmod index	44.9 deg		
TELEMETRY DOWNLINK PARAMETER INPUTS			
Encoding	Reed-Solomon (255,223) concatenated with C.E. (15,1/6)		
Carrier tracking	Residual		
Oscillator	VCO		
Subcarrier mode	Squarewave		
PLL bandwidth	1.00	Hz	
Telemetry usage	Engineering (ENG)—real time		
Telemetry data rate/mod index	3150	bps/ 65.80	deg (38 DN)
Telemetry rng/DOR mod index	0.30	rads/ off	rad
Operations mode	Nominal		
Mission phase	Launch phase		
DSN site	Gold-Gold		
DSN elevation	In view		
Weather/CD	25		
Attitude pointing	EarthPointed		

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Table 6-3. DS1 ranging performance (uplink and downlink) DCT (cont'd).

Produced by DS1 V5.1 12/16/1999					
EXTERNAL DATA					
Range		(km)	3.0816e+08		
Range		(AU)	2.0599e+00		
One-way light time (OWLT)		(hh:mm:ss)	00:17:07		
Station elevation(s)		(deg)	[14.41]		
DOFF: HGA, KHA		(deg)	2.50	2.50	
DOFF: LGA1, LGA2, LGA3		(deg)	2.50	92.50	87.50
Clk: HGA, KHA		(deg)	159.49	0.00	
Clk: LGA1, LGA2, LGA3		(deg)	159.49	0.00	0.00
Added s/c ant pnt offset		(deg)	2.5		
DSN site considered:	DSS-14/DSS-14				
At time:	0.00	hours after the start time			

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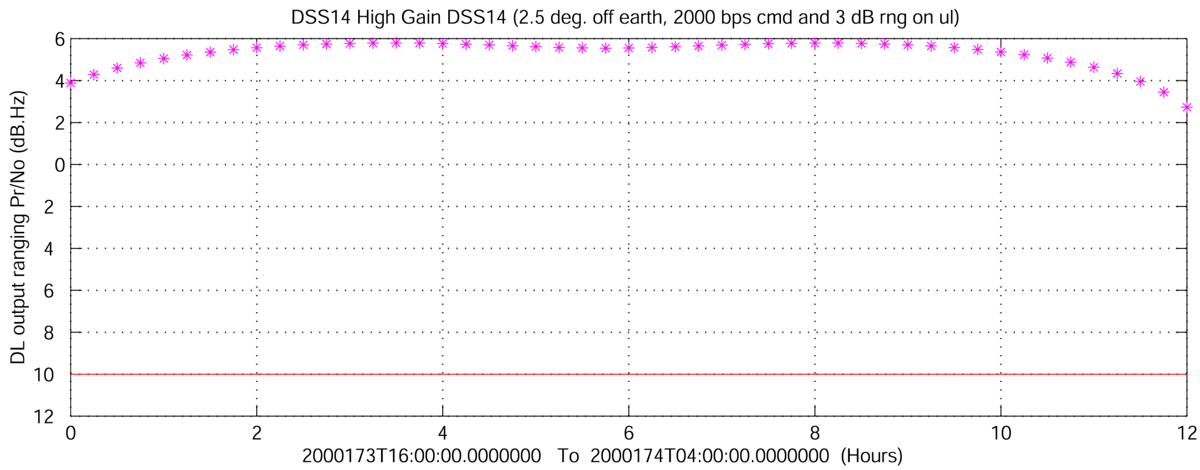
Table 6-3. DS1 ranging performance (uplink and downlink) DCT (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
UPLINK TURNAROUND RANGING CHANNEL						
1. UL recovered Pt/No	dB-Hz	54.89	1.66	–1.66	54.89	0.3063
2. UL cmd ranging suppression	dB	–3.46	0.20	–0.20	–3.46	0.0067
3. UL ranging suppression	dB	–3.03	0.10	–0.10	–3.03	0.0033
4. UL Pr/Pt (2 + 3)	dB	–6.49	–0.30	0.30	–6.49	0.0100
5. UL filtering loss	dB	–0.91	0.20	–0.20	–0.91	0.0067
6. UL output Pr/No (1 + 4 + 5)	dB-Hz	47.49	1.70	–1.70	47.49	0.3229
7. Ranging channel noise BW	dB-Hz	63.22	–0.43	0.20	63.14	0.0176
8. UL ranging SNR (6–7)	dB	–15.65	–1.75	1.75	–15.65	0.3406
DOWNLINK RANGING CHANNEL						
9. DL recovered Pt/No	dB-Hz	38.95	1.30	–1.30	38.95	0.1866
10. Theoretical telemetry suppression	dB	–7.75	0.56	–0.61	–7.76	0.0570
11. Non-linear SDST tlm suppression	dB	–0.57	0.20	–0.20	–0.57	0.0067
12. DL total tlm suppression	dB	–8.34	–0.76	0.76	–8.34	0.0637
13. Theoretical rng modulation loss	dB	–28.30	2.38	–2.46	–28.33	0.9756
14. Non-linear SDST rng mod loss	dB	0.00	0.20	–0.20	0.00	0.0067
15. DL total rng mod loss	dB	–28.33	–2.97	2.97	–28.33	0.9823
16. DL Pr/Pt (12 + 15)	dB	–36.66	–3.07	3.07	–36.66	1.0460
17. DL received Pr/No (9 + 16)	dB-Hz	2.28	3.33	–3.33	2.28	1.2326
18. DL noisy ref loss	dB	0.00	0.00	0.00	0.00	0.0000
19. DL output Pr/No (17 + 18)	dB-Hz	2.28	3.33	–3.33	2.28	1.2326
20. DL out Pr/No sigma	dB-Hz	0.00	0.00	0.00	1.11	0.0000
21. DL out Pr/No mean-2 sigma	dB-Hz	0.06	0.00	0.00	0.06	0.0000
22. DL required Pr/No	dB-Hz	–10.00	0.00	0.00	–10.00	0.0000
23. Ranging margin, mean (19–22)	dB-Hz	12.28	3.33	–3.33	12.28	1.2326
24. Ranging margin, mean-2 sigma (21–22)	dB-Hz	10.06	0.00	–0.00	10.06	0.0000



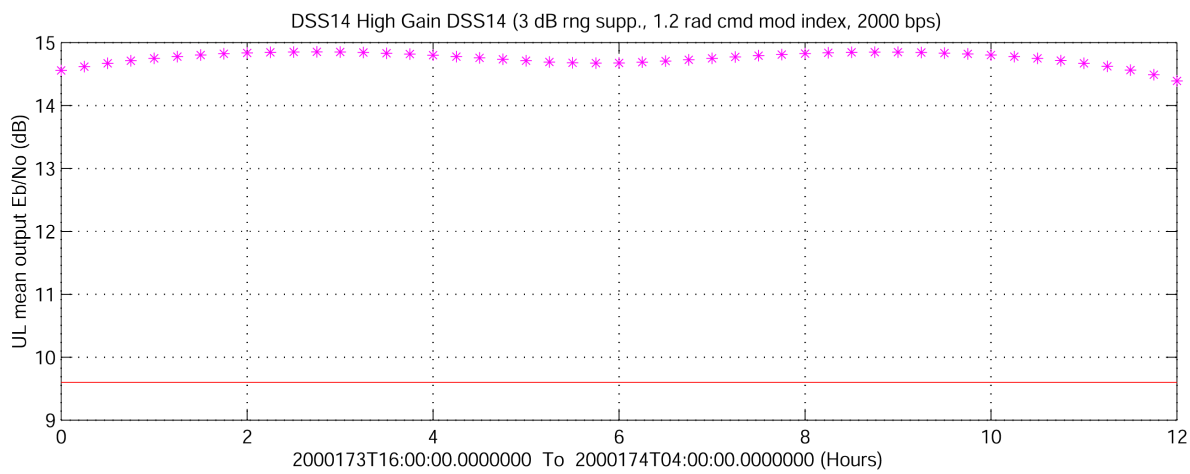


Fig. 6-1. Downlink Pr/No and uplink Eb/No.

The top plot indicates how the ranging performance (predicted as downlink-ranging power to noise-spectral-density ratio) varies during a DSS-14 pass on June 21, 2000. Below a threshold of –10 dB, ranging quality is unacceptable for navigation; below –5 dB, the quality is marginal.

The bottom plot shows the 2000-bps command performance (predicted as uplink-command bit energy to noise-spectral-density ratio) for the same pass. Threshold is +9.6 dB for a bit-error rate of 10^{-5}.

The uplink-ranging carrier suppression is 3 dB, and the command-carrier suppression is –3.5 dB, both standard DS1 values in mid-2000 for 70-m station operation with the spacecraft HGA. The downlink ranging-modulation index is 17.5 deg (low), and the telemetry-modulation index is 65.8 deg. These are also standard DS1 values.

The top plot shows the variation of the DSS-14 elevation angle during the pass on June 21, 2000. Because the signal passes through more of Earth's atmosphere at lower elevation angles,

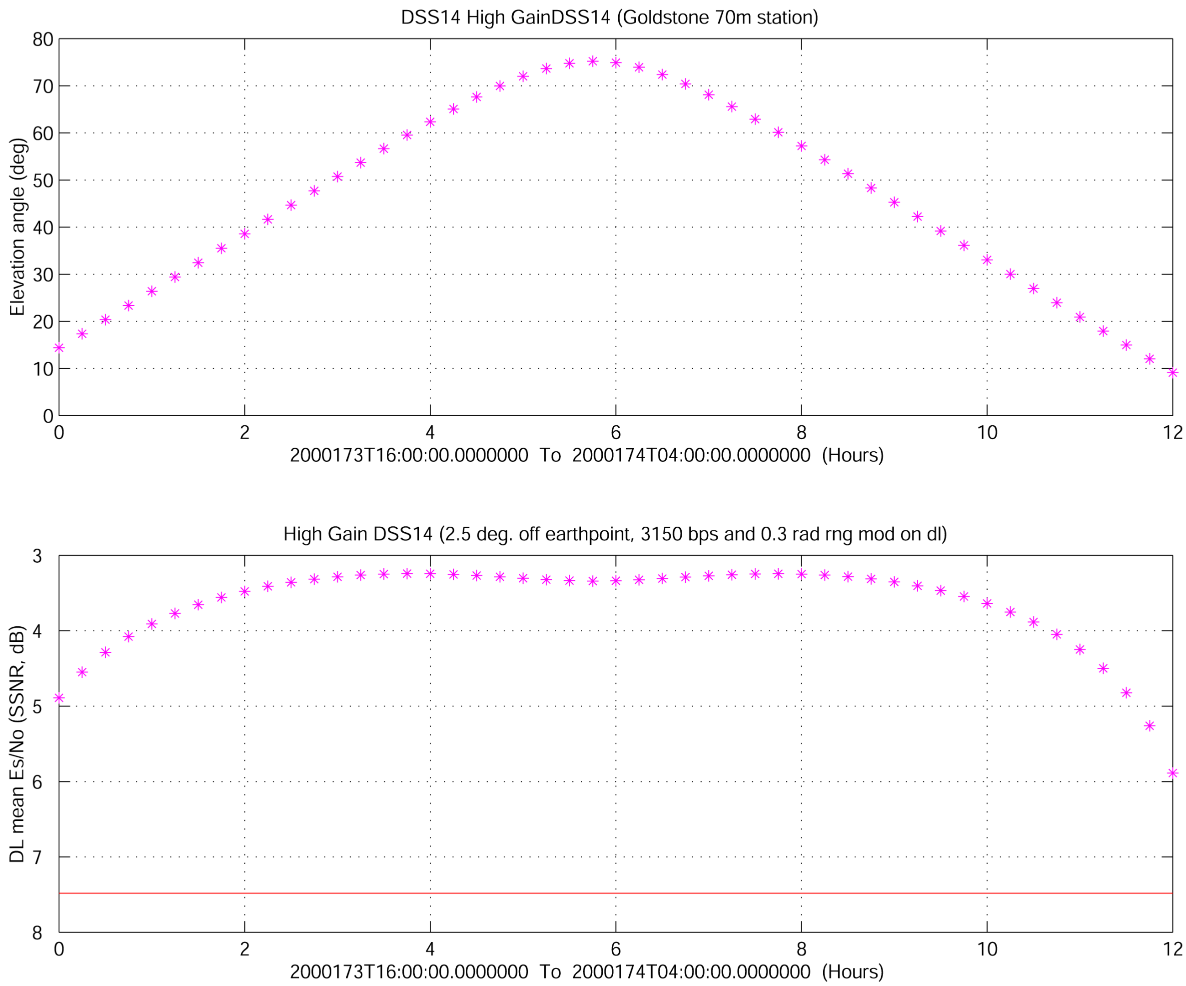


Fig. 6-2. Station elevation angle and downlink telemetry symbol SNR.

the attenuation is larger and the system-noise temperature (SNT) is higher. Attenuation affects both uplink and downlink, while SNT affects downlink.

The bottom plot shows the predicted symbol signal-to-noise ratio (SSNR) of the 3150-bps telemetry. The downlink carrier also has ranging modulation at the “low” index. The telemetry-decoding threshold for the (15,1/6) concatenated code is –7.5 dB SSNR. DS1 experience shows that successful decoding by the MCD3 is improbable when the BVR produces an SSNR lower than –7.5 dB.

Section 7

Operational Scenarios

The following scenarios describe the major telecom-system operating modes in the context of supporting specific phases of the mission or major mission activities and modes.

7.1 Launch

The major prelaunch DS1* telecom operational question was whether to launch with SDST in the coherent or the noncoherent mode. Noncoherent mode (coherency disabled) was chosen. The most important consideration leading to this choice was that noncoherent mode provides an unambiguous downlink frequency for BVR acquisition regardless of whether an uplink is in lock. On the other hand, coherent mode with uplink in lock would have provided immediate two-way Doppler data to determine any corrections from errors in the launch trajectory.

The spacecraft launched with the LGAZ antennas selected, with LGAZ– at the smaller angle to Earth. One day after launch, LGAZ– was to be pointed within about 20 deg of Earth line. The uplink and downlink rates were to provide commandability and telemetry data via the selected LGA over a wide range of pointing errors. At launch, the command rate was 125 bps uncoded. The downlink rate was 2100 bps on a 25-kHz subcarrier, a 40-deg modulation index and (7,1/2) convolutional coding. During the initial acquisition pass, the SDST was commanded to go to the coherent mode (“TWNC [two-way non coherent] off” for the old timers), and to turn the X-band ranging channel on. Approximately one day after launch, the uplink rate was commanded to be 2000 bps, and a small sequence stored onboard before launch was activated to change the downlink rate to 19908 bps, the telemetry subcarrier frequency to 375 kHz, and the telemetry-modulation index to 65.8 deg. That configuration stayed the same for the first two weeks of the mission.

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

7.2 Safing

Safe mode normally occurs when the onboard fault-protection software detects a problem that requires unplanned ground intervention. (A safe-mode configuration can also be commanded intentionally, such as when the flight software is "rebooted" after any software update.)

The original implementation of safe mode for DS1, depending on what fault occurs, would point the +x-axis either at the Sun or at Earth. Since the late-1999 SRU failure, safe mode has always pointed the +x-axis at the Sun and rotated the spacecraft about that axis at a rate of one revolution per hour. The system fault-protection software runs a "telecom script" (an unchanging series of commands, with defined intervals of time between the commands) to configure the SDST, XPA, and the antenna to provide the maximum degree of commandability and chance of a station receiving above-threshold telemetry. Until March 2001, much of the safe-mode telecom configuration (noncoherent mode, 7.8125-bps command rate, 40-bps telemetry rate, 25-kHz telemetry subcarrier frequency, (7,1/2) convolutional coding, ranging off, Ka-band downlink off) was similar to that of the launch mode.

Throughout the mission, the telecom script has been updated as to which antenna it selects and what downlink-telemetry rate it controls. These updates match downlink-performance changes caused by the changing Earth-DS1 distance and Sun-spacecraft-Earth angle. Telecom-script updates are through command-file uploads from the ground. As of March 2001, the script selects LGAX, a telemetry rate of 79 bps, and the (15,1/6) coding. Further changes are not expected through end of mission.

7.3 Anchor Pass (at HGA Earth Point, High Rate)

The term "anchor" refers to the spacecraft stopping its mission activities to point the HGA at Earth and communicate. Anchor passes are scheduled approximately weekly to download telemetry data accumulated since the last anchor pass, to upload new command sequences, and to provide ranging and Doppler data. Prior to the start of the pass, the spacecraft may have been oriented toward a "thrust star" with the IPS thrusting. Since the +x-axis would be off-Earth, minimal communication is possible. The process of pointing to Earth for an anchor pass is based on the use of an onboard algorithm to control the spacecraft-pointing attitude without using the failed SRU. Before start of track, the spacecraft sequence stops the thrusting, turns to an "Earth star" reference so the +x-axis is near Earth, selects the HGA, restarts the IPS thrust,[1] and the X-band downlink (by turning the X-band exciter on). Depending on the amount of telemetry data to be downlinked, the ranging channel may be sequenced on for the entire pass (for less telemetry data), or part of the pass (for more data). One or two hours before the end of an anchor pass, these processes would be reversed: the spacecraft returns to thrust attitude, the IPS is restarted, and (just before the scheduled end of track) the downlink is turned off.[2]

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[1] Thrusting on Earth-point is not usually beneficial to the trajectory but conserves the very limited attitude-control propellant, hydrazine. The IPS is gimbaled in two axes so it can perform attitude control in the x- and y-axes. Thus, while Earth-point thrusting, at a lower level, hydrazine is only expended for attitude control about the third axis (z).

The flight team has developed several variations for starting an anchor pass, based on the degree of pointing certainty at the start of the pass. One variant occurs when the initial Earth-reference star may be more than 5 deg from Earth, or there may be a question about being locked to a star at all. If so, the flight team may elect to start the pass at a low telemetry rate (79 or 600 bps, depending on the uncertainty), with HGA selected but with a "lifeboat" sequence to reselect LGAX after three hours. The telecom analyst would compare telemetry Es/No with the value predicted for the expected off-Earth angle, then recommend a higher telemetry rate to be commanded in real time. If signal level is adequate, the flight team sends a command to "cancel" (deactivate) the lifeboat, and so remain on the HGA.

During sequence planning, the telecom analyst defines for each anchor pass the uplink and downlink rates, together with associated modulation-index values and subcarrier frequencies, and ranging-channel use. The analyst determines the supportable rates, using TFP. During the primary mission, these predicts were in a "data-rate capability file" intended to interface directly with sequencing software. Because confident long-range planning is less feasible when successively chosen Earth-stars are involved, the telecom analyst makes predictions for each pass with the off-point angle input directly. In either case, data rates for each allocated 34- or 70-m pass enter the sequencing process via "service-package files."

7.4 Midweek Pass (at Thrust Attitude for IPS Operation)

Midweek passes alternate with anchor passes, which are usually scheduled for early in the week. During a midweek pass, the spacecraft is three-axis oriented for IPS thrusting through use of the Sun sensor, gyros, and science-camera data (assuming current operations without the failed SRU). During the prime mission, the LGAX or one of the LGAZ antennas dictated required-pointing direction, depending upon which antenna best supported communications on a particular day. For most of the extended and hyperextended missions, LGAX is best because thrust attitudes result in the +x-axis being 0 to 50 deg from Earth. If the angle is less than 7.5 deg, the HGA provides better performance than LGAX. In this case, no turn to an Earth-star is necessary, and HGA communications are possible for midweek as well as anchor passes. For larger angles, midweek passes via LGAX provide at least for the subcarrier tone detection mode to indicate stability of pointing algorithm star-lock and two-way Doppler data to determine if thrusting is still continuing as planned.

As for anchor passes, the telecom analyst predicts midweek pass uplink and downlink performance as a function of time, and 34-m BWG, 34-m HEF, or 70-m station allocation. The top-level spacecraft sequence (the "backbone") for each successive 2- to 3-week period controls the uplink rate and downlink rate to supportable values. The lowest command rate (7.8125 bps) is

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[2] Until April 2001, IPS operation was nearly continuous and at a high-thrust level to reach Borrelly. This thrusting is called "deterministic," with the thrust level determined by the available spacecraft power and thrust direction as a function of time determined by reaching Borrelly at the planned time and miss distance. Subsequently, the mission moved into a period of lower-level "impulse thrusting" for continued hydrazine conservation, using successive orientations at intervals of one or two weeks toward a "north" and a "south" thrust-star, each near an ecliptic pole. Over a period of time, the impulses cancel one another out. Like Earth-point thrusting, impulse thrusting is not at maximum thrust level and so allows the X-band downlink to remain on between passes.

sequenced for 34-m BWG stations with their 4-kW, X-band transmitters. A rate of 125 bps is sequenced for either 34-m HEF stations or 70-m stations, both with 20-kW transmitters. For maximum IPS thrust capability, the X-band downlink is turned on shortly before the scheduled start of track and turned off a few minutes before the end of track. Observing the turnoff validates that the sequence is operating. During midweek passes, the spacecraft is in the coherent mode, to provide two-way Doppler regarding the thrust.

Between tracks, the spacecraft is generally also left in a "distant-pass" configuration so that if an unscheduled pass should become necessary, DS1 is commandable. The distant-pass configuration in late 2001 was LGAX, 7.8125-bps command rate, and 79-bps telemetry rate.

7.5 High-Gain-Antenna Activity (January–June 2000, March 2001)

DS1 spacecraft was launched with a Sun-sensor assembly (SSA), inertial measurement units (IMUs), and the previously mentioned SRU; together they provided three-axis control of spacecraft pointing.[3] During the prime mission and until November 11, 1999, when the HGA was selected for planned operations, it was pointed at Earth within a normal dead-band tolerance of 1 deg.[4] That day, downlink performance was not consistent with the HGA and the Earth-point planned for that pass. The spacecraft was found to be in safe mode (LGAX selected and x-axis pointed to the Sun) after a tracking station could not acquire the expected downlink. Subsequent telemetry analysis showed the SRU was inoperative. Afterwards, the spacecraft remained in safe mode for some months, and low-rate uplink and downlink communications were done via LGAX.

To return valuable science data already stored onboard at the time of the failure, as well as moderately-voluminous engineering data concerning the failure itself, the project flight team invented a ground-in-the-loop method to point the spacecraft close enough to Earth to use the HGA. The name refers to the operation of feedback-control loops with delay. Here human analysts analyze spacecraft and station data in real time, then send corrective commands immediately in real time, all the while constrained by the tens of minutes of delay inherent in the light-time between Earth and the spacecraft. Fundamental to ground-in-the-loop control is the idea of moving the spacecraft from its +x-axis to the Sun attitude to +x-axis near Earth. This was accomplished with a combination of inertial-control and attitude-control system inputs from the gyros and the SSA only. The first part of the process is determining the position (stop the antenna); the second part is maintaining the position (keep the antenna pointed).

This special mode is described in some detail because it involves considerable use of the telecom-analyst's skills in monitoring and assessing the significance of variations in downlink-signal levels. The most basic measurement is of carrier performance as represented by the Pc/No (carrier power-to-noise spectral-density ratio). The analyst assesses in real time what com-

[3] The SSA was not used for three-axis control or knowledge in normal operation. Only the SRU and IMUs were used in normal operation.

[4] The term "dead band" comes from feedback-control theory. It refers here to an angle (1 deg) relative to the deviation of the actual pointing relative to each desired axis (x, y, z). When the difference between actual and planned pointing about an axis reaches the dead-band limit (say +1 deg), the control system fires a thruster in the negative direction. No corrective action occurs so long as the pointing error remains within the dead band.

mands to send and when to send them. The commands are used to change basic spacecraft motion and pointing. The initial motion is called “coning,” which is rotating the spacecraft around the line joining the Sun to the spacecraft, with the +x-axis at a fixed-offset angle from the Sun (equal to the Sun-spacecraft-Earth angle). The rotation (coning) rate is once per 45 min.[5] When coning is stopped, the final motion is with the +x-axis pointed “near” Earth, under inertial control. Pointing control commands index the +x-axis by a selected number of degrees (from 2 to 8), to compensate for gyro drift during the hours of the pass.

7.5.1 Stopping the Antenna Near Earth by Using the Planning Worksheet

Use of an Excel-planning spreadsheet requiring only simple and rapidly made inputs and providing simple and unambiguous-to-use outputs is essential to achieve the initial HGA pointing, starting from the +x-axis to the Sun condition. See Fig. 7-1.

Before the pass begins, the telecom analyst customizes the spreadsheet with the allocated start-and end-track times, the “start coning” and “final conditions” sequence start times, and the one-way light time. Figure 6-1 shows one-of-three parts of the worksheet, with the times in the two “action” cells updating as soon as the analyst has filled in the “observe” time. The two actions are (a) the time the station will turn on its transmitter and begin an uplink-acquisition sweep, and (b) the time the DS1 controller (ACE) will radiate the “stop-coning” activate command.

The onboard “start-coning” sequence puts the spacecraft into an attitude-control system mode that ensures the HGA will sweep its boresight past Earth periodically. The telecom system is switched from LGAX to HGA, telemetry modulation is removed from the downlink carrier, and the command rate is set to 31.25 bps. The +x-axis moves from the Sun, a distance equal to the Sun-spacecraft-Earth angle, and the spacecraft is sequenced to begin rotating about the Sun-spacecraft line at one rotation per 45 min. Using the spreadsheet to determine the actual rotation rate, the telecom analyst observes and times the occurrence of two sweeps of the HGA boresight past Earth, and then gives the ACE the “action” times. These determine when the uplink and the command must be sent to reach the spacecraft, as the HGA is pointed near Earth the third time. Excluding station problems, 95 percent of the time this process stopped the antenna near Earth on the first attempt.

The March 2001 HGA activity was planned to stop the antenna, based on the analyst’s seeing only one peak, on the assumption that the rotation was always close to once per 45 min. This “single-peak” activity, which was checked against the similar one in June 2000, was successful.

7.5.2 Keeping the Antenna Pointed Near Earth by Monitoring Signal Levels

The quantities monitored during this phase include the downlink Pc/No, telemetry Es/No (symbol energy to noise-spectral-density ratio), or uplink Pc (carrier power).

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[5] The coning rate is one rotation per 45 min. in contrast to the safe-mode rotation rate of one revolution per 60 min. As part of the SRU recovery flight-operations redesign, the coning rate was made as rapid as possible while still providing sufficient time to get a “stop-coning” command to the spacecraft. The safe-mode rate was established before launch, and there has been no reason to change it.

Action Plan (based on seeing first 2 peaks)									
act_date	05/26/00								
owlt_sec	981								
owlt=	0:16:21								
rtlt=	0:32:42								
time/rev=	0:44:39	(from 1st to 2nd observed peak)						**NO**	coherency?
typeover seeded items				Do **NOT** enable uplink station Conscan				**NO**	ka-band dl?
type in observations				planned times/intervals				**NO**	fsr recording?
station		**NOCC**	**QUERY**					**NO**	ul conscan?
transmit	**SCET**	**receive**	**receive**	**what**	**dB or time value**				
		12:23:41	**12:23:41**	**observation: 1st HGA peak used in stopping HGA**					
		12:23:26		observation with delay removed					
		13:08:41		2nd HGA peak was expected			nominal =	00:45:00	
	observe-->	**13:08:20**	**13:08:28**	**observation: 2nd HGA peak used in stopping HGA**			**interval=**	**0:44:39**	(2nd - 1st peak)
		13:52:59	13:53:07	3rd HGA peak expected					
13:20:05		13:52:47	13:52:55	expected 3rd peak with delay removed					
13:11:20				Start Excel sheet update (2nd peak seen plus 1 min)			**worktime=**	**0:06:00**	
13:13:20	**<--alert**			Give ACE station drive_on time					
13:13:20				ACE verifies CMD buffer selected for 31.25 bps			nominal =	00:11:19	
13:18:20	**<--action!**		**13:18:28**	34m station's transmitter drive ON			**interval=**	**0:10:00**	(DrvOn - peak)
				start sweep (3 segments +/-10 kHz, 300 Hz/sec = 00:01:40 for sweep)					
13:20:00				Expected end of sweep (based on **ACQ** and nominal **ETX30XCN** duration of 00:01:40)					
13:20:05				Station turns command modulation ON at end of sweep					
13:20:12				ACE verifies command modulation ON			nominal =	00:13:24	
13:20:25	**<--action!**		**13:20:33**	"Stop coning" activate cmd bit1 (drive ON + 00:02:05)			**interval=**	**0:12:05**	(Bit1 - peak)
13:20:28				Actual radiation begin, including command system latency					
13:20:52	13:37:13			End radiation of activate command (for 31.25 bps only, excluding vc5 tail sequence)					
13:20:53	13:37:14			Sequence execution begins					
13:20:53	13:37:14			Sequence execution completes					
13:21:45	13:38:06	13:54:27		WAG: HGA stops.	0:01:40	after **real**	3rd peak		
		13:55:09	**13:55:17**	Stopped HGA expected	**00:02:10 nominal**		0:00:42	(stop - peak)	
		14:00:29	**14:00:37**	HGA turn back expected	**00:05:20 nominal**		0:05:20	(back - stop)	
Change log									
1/18/00	**See "1stPeak_plan_times" for general updates**								
4/26/00	**No Conscan on uplink station**								
5/5/00	**Added planning intervals for "stop coning"**								
5/12/00	**Corrected erroneous definition of owlt in 2ndPeak sheet**								
5/12/00	**Defined drive_on warning = 5 minutes (was 2 minutes)**								
5/12/00	**Define start_excel time = 2ndPeak obs + 1 min, based on NOCC RT (was 3 min)**								
5/15/00	**Change "give ACE..." cell A23 to "alert" and color yellow**								
5/15/00	**Add rows 37-38 for expected HGA stop and HGA back to earth**								

Fig. 7-1. Replica of "HGA Activity Planning Spreadsheet" for May 26, 2000 activity.

After the ACE has radiated the "stop-coning" command, the telecom analyst records the Pc/No observed for each of the first two peaks from each of the two receivers. This single command activates a small stored sequence of commands that stops the coning rotation, produces a turn-back in the opposite direction to return the HGA to near-perfect Earth-point, and resets the command and telemetry rates for further activity. The analyst compares the Pc/No value against the mean value predicted by TFP that assumes the HGA boresight is Earth-pointed with all telecom-link components operating at their expected values. The purpose of this assessment is to estimate the maximum downlink rate the link can support, taking into account link performance as well as the HGA-pointing control demonstrated during previous HGA activities.

Next, the station Pc/No data show the third peak, the subsequent halt in antenna motion, and the turn back to Earth. The telecom analyst directs the ACE to command the activation of a stored "telemetry-rate" sequence to establish the supportable rate, with its subcarrier frequency and modulation index. Thereafter, through the remaining hours of the pass, the analyst continues to monitor downlink Pc/No, Es/No, and uplink Pc to determine if the antenna drifted too far from Earth to support the rate. If so, the analyst directs that a "corrective-turn" activate command be transmitted. The criterion for activating a "corrective-turn" sequence is if the Es/No first falls to –6 dB (with the threshold being –7.5 dB) fairly rapidly or sinks to –6 dB twice but less rapidly.

The March 2001 HGA activity, using the new flight software, progressed similarly to many HGA activities in 2000. For the first few hours after Earth-point was achieved, the HGA remained near Earth. Gradually, pointing became worse, and ordinary-corrective turns were not effective. Seeing this, the DS1 attitude control analyst developed a new-turn sequence that mimics a fraction of a turn of the original-coning rotation. This sequence restored HGA pointing, and has been made standard for HGA activities required after future safe-mode events, or flight-software updates.

7.6 Solar Conjunction

Solar conjunction occurs when the spacecraft and the Sun are in the same angular region as viewed from the deep-space station [17]. The angular separation is the Sun-Earth-probe (SEP) angle. Effects on deep-space communications become more severe as the SEP angle becomes smaller.[6] For DS1, X-band up- and downlink, we considered an angle of 5 deg as the minimum at which to expect no degradation, and 3 deg as the minimum at which reliable communications could be planned. From October 20 to December 3, 2000, the angle was less than 5 deg, and from October 29 to November 25 it was less than 3 deg. The minimum angle was less than 0.5 deg during a scheduled pass on November 14, 2000. The 11-year solar cycle was near its maximum.

Both to minimize configuration changes, and to use the HGA as much as possible, project navigation found a single-reference star with small x-axis-to-Earth angle throughout the conjunction period.[7] The HGA off-point from Earth varied from about 2.5 deg at period start to a minimum of 0.3 deg November 13, to about 2.8 deg at period end. The first scheduled postcon-

[6] A superior solar conjunction (like DS1's) occurs when the Sun is between the spacecraft and the Earth. Planning for superior conjunction effects on deep-space links at JPL currently takes into account only the carrier-frequency band and the Sun-Earth-spacecraft angle. Solar activity varies in cycles, with the 11-year solar cycle near a maximum in 2000–2001. The effects on a link, caused by charged particles from the Sun producing amplitude and phase scintillation, may also be highly variable over periods of a few minutes to a few hours. Coronal-mass ejections (CME) of charged particles that cross the ray path between Earth and the spacecraft have degraded Galileo low-margin S-band links even when the SEP angle is large (> 90 deg). Apparent solar effects affected DS1 X-band up- and downlink signals during a pass on April 3, 2001 (at SEP ~31 deg), less than one day after a very large (class X20) solar flare occurred.

junction pass that the project was able to receive telemetry was on November 20, with the Sun-Earth-spacecraft angle at 1.1 deg.

The DS1 project planned the solar conjunction as a single sequence with minimal configuration changes, to be loaded onboard for execution for the entire duration. The up- and downlink data rates were conservative, and the command-loss expiration was pushed to beyond the time the angle would again be greater than 3 deg. The command rate was made 7.8125 bps through the conjunction period.

Downlink strategy, as a function of Sun-Earth-spacecraft angle, was to:

- Sequence a downlink rate that was reduced by one or two data rates from normal between an angle of 3 and 5 deg. For example, instead of 4424 bps, sequence 3150 bps or 2100 bps. Instead of 790 bps sequence 600 bps or 420 bps. This increased the margin by about 1.2 to 3.1 dB
- Sequence 40 bps for passes with an angle less than 3 deg
- Modulate downlink carrier with only a subcarrier tone for passes with an angle less than 1 deg.

Link configurations were based on experience from recent solar conjunctions of Mars Global Surveyor and Cassini, as well as on the recommendations of David Morabito, of the JPL Telecommunications Systems and Research Section. The sequence included operating both the X- and Ka-band downlinks. It also included periods with the downlink in the two-way coherent mode (SDST-coherency enabled and uplink in lock) and other periods with no planned uplink. The objective was to maximize the probability that at least one frequency band would be receivable during the scheduled weekly tracking passes. The strategy was successful both in monitoring spacecraft health and providing open- and closed-loop data for telecom analysis, and planning other project conjunctions [17].

7.7 Ka-Band Downlink

Using the Ka-band downlink during the first months after launch was for technology validation of the KaPA. Ka-band was also used operationally during portions of the solar conjunction in November 2000. The Ka-band downlink is receivable via the KHA only when the +x-axis points at Earth and a station with Ka-band capability has been allocated. Sequencing of the Ka-band exciter of the SDST and the KaPA is through previously stored commands.

During the 1998–99 technology validation period, the Ka-band downlink carried telemetry and ranging data. Ranging channel on/off and modulation index (low/high) are individually controllable for X- and Ka-band, as is the telemetry subcarrier frequency and modulation index. However, only a single downlink rate is available at a time for use on both bands. Because the KHA and HGA gains are similar, but the KaPA has one-fifth of XPA's RF output, the Ka-band

[7] Part of the rationale in selecting the reference star used during conjunction was to yield good pointing relative to Earth for the November 20 pass. The star was also suitable for IPS thrusting which continued throughout conjunction. The 0.3 deg minimum Sun-Earth-spacecraft angle that occurred on November 13 compares with a solar radius of about 0.25 deg and meant the signal path from spacecraft to Earth was very nearly blocked by the Sun.

supportable telemetry rate is similarly reduced relative to X-band. Because DS1 is downlink-rate limited, the project generally chooses the higher rate supportable on X-band. Subsequently, except for special tests, the Ka-band downlink has been unmodulated.

Section 8

Lessons Learned

8.1 Telecom-Related Lessons Learned

In December 1999, Telecom presented lessons learned to DS1*. This section is an update of that material, covering the development and testing of the SDST and KaPA, as well as the flight operations. The section begins with some things we did mostly right and ends with other things that caused us difficulty.

8.1.1 Telecom Pre-Launch Testing

Telecom hardware testing by the manufacturer, the JPL Telecom-Development Lab (TDL) system testing, DSN-compatibility testing, and spacecraft-level prelaunch system testing was thorough enough on DS1 that the flight team has yet to find an untested SDST characteristic that is needed for in-flight planning or analysis. The DS1 telecom test plan should be used as a model for our in-development projects. Future test plans don't need to include repeats of development tests already done for unchanged components; however, the planning needs to be equally thorough in considering the telecom functions (command, telemetry, carrier tracking, including the presence of Doppler shifts, ranging) and mission plans.

8.1.2 Development-to-Operations "Handover"

This was properly scheduled and well executed. The flight-team telecom analyst came onboard a year before the planned launch, and the development telecom-system people remained to lend a hand through the planned "40-day" technology-validation period that lasted six months. The intense period of telecom in-flight characterization (planning and execution) probably lasted half that long, with the formal SDST, KaPA, and BMOX technology-validation activities on the spacecraft occupying all or portions of about 15 passes. The telecom analyst was well seasoned by launch, including a sufficient familiarity with the DS1 spacecraft and specifically its telecom system characteristics. Even so, the telecom-development engineers played

*Look up this and other abbreviations and acronyms in the list that begins on page 60.

important roles in the formal-technology validation. Plans for our in-development projects need to include a development-to-operations handover of at least one year.

8.1.3 Flight Team Telecom-Support Level

The flight-team plan for telecom staffing was 1.0 full-time equivalent (FTE) in the prime mission, reducing to 0.5 during the extended mission. The reality was the need for 1.5 to 2.0 FTEs; through in-flight characterization, remaining at 1.0 through the SRU-anomaly resolution, and 0.75 by May 2001. Some causes: our software tools were not mature; there is more than expected hands-on flying of this dynamic spacecraft; and there is a continuing need to produce two forms of telecom-configuration definitions (a DSN keywords file and service packages). The DS1 experience taught us that we need a full-time, seasoned telecom analyst for each spacecraft, with moderately active telecom planning and execution, with tracking a half or more of the total time. This level can begin to be cut back once several projects have a common set of automation tools for telecom planning and analysis.

8.1.4 Effective Staffing Mix

On DS1, the senior-lead telecom analyst trained and mentored two junior analysts successively through the prime mission. We verified that routine or repetitive tasks such as performance-comparison runs do not require a senior analyst. A second, on-call senior analyst can step in for vacations, illness, etc. DS1 hoped to do the link-analysis task using a pool of qualified engineers. However, this “plug and play” approach did not work for DS1 because there were never enough members in the pool, and there were not enough projects subscribing to the concept. The implication here is that these problems have to be overcome to make a pure “service” approach work, and—even then—a senior analyst with continuity on each project is vital to mission success for a telecom-active mission. In the future, availability of more effective or integrated telecom software would allow for automation of the routine tasks, requiring only a review of the results by a less senior analyst.

8.1.5 Flight Team Co-Location, Near the MSA

Operating from a separate building by telephone and e-mail would not have worked. Co-location reduces sequence-integration/review turnaround-time during iterations. The data are accessible only behind the firewall in the MSA. Interruptions are a resultant co-location cost in individual-analyst efficiency. These results underscore the lesson that the planning portions of the link-analysis task are project-dedicated flight-team functions, not a generic task.

8.1.6 Effective, Easy-to-Use Data Displays

DS1 made a formal agreement with the DSN to provide access in the MSA to operate (via graphical user interface) the workstations of the DSN’s Network operations control-center real-time (NOCC RT) system. This allows a telecom analyst or the ACE to resolve configuration and bandwidth problems. Because of the demonstrated need for it on DS1, the AMMOS system has developed some NOCC RT functions, including plot rescaling without data loss, in the DMD.

8.1.7 Querying Data

The AMMOS query system has limitations, particularly for even a few telemetry channels over long durations. Consequently, to complete the technology validation required 2-1/2 weeks of senior-analyst time for queries of KaPA performance and configuration back to the time of the in-flight characterization (December 1998). The set of tools, DMD/EZquery/Oplot is capable, but it works easily only for fairly recent data (of a few weeks' duration).

8.1.8 Telecom-Sequencing Standardization

Inconsistency in telecom configuration guidelines led to the need to redeliver service packages (SPs) and to re-review sequence products. On the other side, there was a real growth over time in sequence modularization and standardization through use of activity types such as the TBOT and TEOT (telecom at beginning and end of tracks), downlink-rate control (including ranging-channel use, modulation index, and subcarrier frequency), and the DSN keyword files (DKFs). Dual lessons here are to (a) publish sequence-generation guidelines early and stick to them, and (b) modularize for reuse the sequence elements at several levels higher than individual commands.

8.1.9 Need for an As-Flown Sequence

A project needs a good one-page-per-day SFOS (spaceflight operations schedule) for planning and a good as-flown SOE (sequence of events) for analysis. An as-flown set of sequenced and real-time telecom commands could replace data queries to establish configuration for technology validation or problem analysis.

8.1.10 Simultaneous Update

Selection of TFP (over Excel) was the correct choice for the solid tool needed for the operational environment, but it was new software. In the several months before and after launch, there were several deliveries of TFP as well as the need for individual "add path" telecom models.[1] Up to several hours of analyst time are needed to verify the correctness of each add-path update and several days to verify a formal TFP delivery before use in project-mission planning. The nonlinearity in the flight-engineering model SDST X-band modulator [18] required 1-1/2 months for users to determine how to model and implement in TFP. Most of these TFP-development "growing pains" should be less severe for in-development projects that adapt the same tool. The DS1 lesson is that the project-development plan needs to provide for a sufficient adaptation, debug, and shakedown effort for a new link-analysis tool ensemble.

[1] See [15] for a description of TFP, including "add path." The name refers to maintaining the officially-delivered TFP spacecraft and station models in specific computer directories, then establishing updated models, as needed, in separate directories. TFP allows the user to specify that a TFP run use the updated model by adding its directory path to the run instructions. For example, when many station performance parameters and models changed as the interface document 810-5 was updated from [13] (Rev. D) to [12] (Rev. E), the DS1 telecom analyst has used add paths for the more significant differences such as 70-m station system-noise temperatures.

8.1.11 Service Packages and DSN Keyword Files

As part of a ground-system "new technology," DS1 worked with the DSN to define the SP for both the telecom-configuration input to project-sequence planning and the project input to the new Network Planning and Preparation (NPP) system. The NPP, intended as an automated means for station-configuration management, never became operational. As DS1 launch neared, significant concern about the NPP development resulted in a TMOD/project agreement for the project to use the older DKF station-configuration-management input. The project used SPs for telecom input to the sequencing process, as planned. Telecom time was lost before launch to develop and test the SP as an NPP input. With hindsight, a telecom interface for project sequence input only, could have been less complex than the SP. The late changeover to the DKF interface resulted in the need for several updates to the DKF-generation software through flight, and still a need for some hand-editing and a review of DKF outputs. The DS1-SP experience will be applied to our in-development projects to make their data-rate-capability generation, configuration trade-off, and telecom-planning input processes and tools simple to use and easy to modify. At the other end of the sequence-generation process, the DKF-interface to DSN configuration needs to be made both significantly more flexible (allowing for several data rates per pass) and more automated than it became on DS1.

8.2 Project-Level Lessons Learned

In December 2000, the former and current DS1 project managers and the spacecraft-development system manager presented the "lessons learned" to JPL [19]. The presentation included a mission summary, a discussion of the mission-success criteria, and the spacecraft-system-development schedule to place things into context.

Following one page titled, "Why did DS1 accomplish so much?," and another two titled, "What worked well?," there are 12 pages headed, "What didn't work well and why?"

Here, from that presentation, is a summary of the DS1 project-level lessons learned. Without the inclusion of the events that motivated each lesson, these should be taken more as a checklist for deep-space project operations in the future.

8.2.1 Project Management

- A project needs at least a year for Phase A/B, culminating in a review to ensure the mission concept is sound, the requirements are agreed to, and there are sufficient resources to do the job.
- During the early project phases, define phasing of funding, need dates for the launch vehicle, requirements and success criteria, etc., and do not proceed with further commitments until the entire project is better understood and agreement is in place with NASA Headquarters.

8.2.2 Organization-and-Team Dynamics

- The team is the most important factor in mission success.

- An unambiguous organization, adequate resources and the right environment are essential to allow the team to succeed. It is critical to have adequate resources to allow the team to do their job in a humane way.

8.2.3 Reviews

- Peer Reviews add the most value.
- Set up a peer-review plan early and get line-management support. Make sure the industry partner buys into the peer-review process.

8.2.4 Advanced Technologies

- Develop a technology plan during formulation that addresses risk-mitigation and technology readiness. Include meaningful technology-readiness gates to assess development progress, include clear-action plans if the gates are not met.
- Be cautious about having one technology rely on another for testing.
- If technologies are coupled, treat the independent technology as critical.

8.2.5 Communications and Data Transfer

- Require data transfer to occur at the technical level, without intermediaries.

8.2.6 Assembly, Test, and Launch Operations

- Include adequate margin in development schedules, particularly for technology development. Develop an Assembly, Test and Launch Operations plan that is resilient to late deliveries.

8.2.7 Operations

- Resources (personnel and schedule) need to be made available in order to allow spacecraft-and payload-team participation early in operations planning.
- Allocate time to allow development personnel to complete integration and test activities and to prepare for mission operations.

8.2.8 Contingency Procedures

- Develop contingency procedures and update them during development and operations as new information makes them obsolete.

8.2.9 Operations-Testbed Environment

- If an activity is important and uncertain enough to test in a test bed, then require all subsystems with major involvement in it to review the test results.
- The test-bed configuration should be as flight-like as possible, and differences must be completely understood by the operations team.

8.2.10 Single-String Teams

- Build in human redundancy.
- Allocate funds for training and mentoring. Identify this as a major risk if the budget will not allow additional staffing.

8.2.11 External Communications

- Define and maintain clear lines of communication to management and to the news media. Communicate the probable outcome of critical events and their impact clearly to JPL, Headquarters, and the media.

8.2.12 Science in a Technology-Validation Mission

- Speak clearly as a project, with one voice, to ensure that external expectations match priorities. Project, JPL and Headquarters must be in agreement on mission-success criteria.

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Abbreviations and Acronyms

ACE	call sign for project real-time mission controller
AGC	automatic gain control (received carrier power)
AMMOS	Advanced Multimission Operations System
ATLO	Assembly, Test and Launch Operations
BBPP	base-band patch panel
BER	bit-error rate
BMOX	Beacon-Monitor Operations Experiment
bps	bits per second
BVR	Block V Receiver
BW	bandwidth
BWG	beam waveguide
CAS	Cassini Project
CD	cumulative distribution
CDR	Central Data Recorder
C&DH	command and data handling
Clk	clock
CMA	command modulator assembly
Cmd	command
CMD	command system
CME	coronal-mass ejection
CNR	carrier-to-noise ratio
CPA	command processor assembly
dB	decibel
DCT	design control table
DKF	DSN keyword file
DL	downlink
DM	data mover
DMC	DSCC meteorological computer
DMD	data monitor and display
DOFF	degrees off (boresight)
DOR	differential one-way ranging
Drv	drive

DS1	Deep Space 1
DSCC	Deep Space Communications Complex
DSMS	Deep Space Mission Systems
DSN	Deep Space Network
Eb/No	bit-energy-to-noise spectral-density ratio
EIRP	effective isotropic radiated power
ERT	Earth received time
Es/No	symbol energy-to-noise spectral-density ratio
ETX	exciter transmitter
FEM	flight-engineering model
FSR	Full-Spectrum Recorder
FSS	Frame Synchronizer System
FTS	frequency and timing system
GaAs	gallium arsenide
GUI	graphical user interface
HEF	high efficiency
HEMT	high electron mobility transistor
HGA	high-gain antenna
HLAN	high-speed LAN
ICA	IF channel assembly
IDS	IPS diagnostic sensors
IEM	integrated-electronics module
IF	intermediate frequency
IMU	inertial-measurement unit
IPN-ISD	InterPlanetary Network and Information Systems Directorate (formerly TMOD)
IPS	ion-propulsion system
ISU	International Space University
JPL	Jet Propulsion Laboratory
LAN	local-area network
LCCD	level clock conversion distribution (interface)
LCP	left-circular polarization
KaPA	Ka-band power amplifier
KHA	Ka-band horn antenna
LGA	low-gain antenna
LGAX	LGA directed along the +x-axis
LGAZ	LGA directed along the +z-axis
LGAZ–	GA directed along the –z-axis
LMC	link monitor and control

LNA	low-noise amplifier
LPE	low-power electronics
MCD	maximum-likelihood convolutional decoder
MDA	metric data assembly
MICAS	miniature integrated-camera spectrometer
MON	monitor system
MST	monitor sample time
NAV	navigation
NMC	Network Monitor and Control
NMP	New Millennium Program
NOCC RT	Network Operations Control Center real time
NOP	network operations plan
NPP	Network Planning and Preparation system
OWLT	one-way light time
PASM	power actuation and switching module
Pc/No	carrier power to noise-spectral-density ratio
Pd/No	Data power-to-noise spectral-density ratio
PEPE	Plasma Experiment for Planetary Exploration
PLL	Phase-lock loop
Pr/No	ranging power-to-noise spectral-density ratio
Pt/No	total power-to-noise spectral-density ratio
PR/TSA	project requirements/TMOD support agreement
RAX	Remote-Agent Experiment
RCC	receiver control computer
RCP	receiver channel processor
RCP	right-circular polarization
RF	radio frequency
RLAN	receiver LAN
RNS	reliable network service
RS	Reed-Solomon
RTLT	round-trip light time
S&L	standards and limits
S/C	spacecraft
SCARLET	Solar Concentrator Array Using Refractive Linear Element Technology
SCET	spacecraft event time
SDST	Small Deep-Space Transponder
SEP	solar-electric propulsion (technology)
SEP	Sun-Earth-probe (angle)

SFOS	spaceflight operations schedule
sigma	spelled out form of Greek character, σ (for 1 standard deviation)
SIT	select in test
SNT	system-noise temperature
SOE	sequence of events
SP	service package
SPC	signal processing center
SRA	sequential ranging assembly
SRU	stellar-reference unit
SSA	Sun-sensor assembly
SSD	symbol stream distribution
SSK	soft symbol controller
TBOT	telecom at beginning of tracks
TEOT	telecom at end of tracks
TCA	telemetry channel assembly
TFP	telecom forecaster predictor
Tlm	telemetry
TLM	telemetry system
TMOD	Telecommunications and Mission Operations Directorate (now called IPN-ISD)
TRK	tracking system
TWNC	two-way noncoherent
UL	uplink
USO	ultrastable oscillator
UTC	universal time coordinated
VC	virtual command
VCO	voltage-controlled oscillator
VME	Versamodule Eurocard
WAG	rough engineering estimate
Xe	xenon
XPA	X-band power amplifier